Geol Survey

ISGS CONTRACT/GRANT REPORT
1987-1

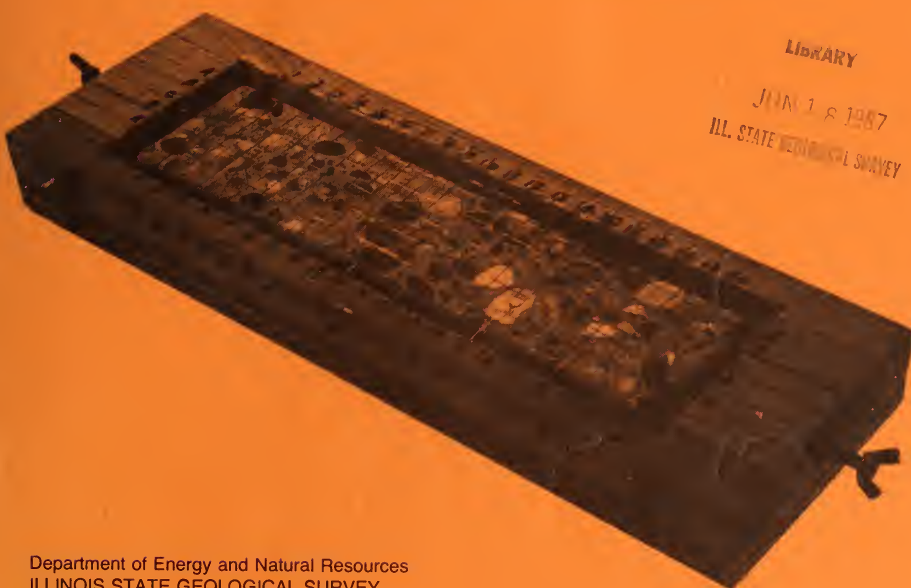
ILLINOIS DEPARTMENT OF TRANSPORTATION
PROJECT IHR-416

Final Report

Geologic characteristics of Illinois gravel deposits affecting IDOT freeze-thaw test results

John M. Masters and R. Douglas Evans

in cooperation with the
Illinois Department of Transportation



Department of Energy and Natural Resources
ILLINOIS STATE GEOLOGICAL SURVEY
March, 1987

Drafting: John Moss

Masters, John M.

Geologic characteristics of Illinois gravel deposits affecting IDOT freeze-thaw test results / John M. Masters and R. Douglas Evans in cooperation with the Illinois Department of Transportation. — Champaign, IL : Illinois State Geological Survey, 1987.

ix, 85, 13 p. ; 28 cm. — (ISGS Contract/Grant report ; 1987-1)

1. Gravel—Illinois. 2. Gravel—Testing. 3. Gravel—Geology—Illinois. 4. D-Cracking. I. Evans, R. Douglas. II. Illinois Department of Transportation. III. Title. IV. Series.

Printed by authority of the State of Illinois/1987/400

ISGS CONTRACT/GRANT REPORT
1987-1

ILLINOIS DEPARTMENT OF TRANSPORTATION
PROJECT IHR-416

Final Report

Geologic characteristics of Illinois gravel deposits affecting IDOT freeze-thaw test results

John M. Masters and R. Douglas Evans

in cooperation with the
Illinois Department of Transportation

ILLINOIS STATE GEOLOGICAL SURVEY
Morris W. Leighton, Chief
Natural Resources Building
615 East Peabody Drive
Champaign, Illinois 61820

ERRATUM

John M. Masters and R. Douglas Evans in cooperation with the Illinois Department of Transportation, 1987, Final Report, Geologic Characteristics of Illinois Gravel Deposits Affecting IDOT Freeze-Thaw Test Results: Illinois State Geological Survey, Contract/Grant Report 1987-1, 84 p. plus appendices.

Authors should be John M. Masters, R. Douglas Evans, and Jennifer K. Hines in cooperation with the Illinois Department of Transportation.

TABLE OF CONTENTS

TABLES

FIGURES

ABSTRACT

The Illinois Department of Transportation (IDOT) initiated the freeze-thaw test (ASTM C666-77) as an additional quality control in order to eliminate "D-cracking" from Portland cement concrete highways in Illinois. The objective of this joint research project of the Illinois State Geological Survey and IDOT was to identify the rock types in gravels that cause the expansion of freeze-thaw test beams and the variability of the expansion data.

Samples were collected from various gravel producing areas and studied by (1) identifying and tabulating data on pebbles in the surfaces of slabs cut from test beams, and (2) separating gravel by rock types and independently freeze-thaw testing them in groups. Statistical analyses of the rock-type data indicated that chert, especially low-specific gravity (<2.35) chert, and ironstone, along with silty dolomite, and possibly weathered carbonate are the most expansive rock types in the gravels studied. Variability of the freeze-thaw expansion data is probably due to nonrepresentative assortments of expansive pebbles located in the critical central core of the test beams, and subtle variations of rock types within the sand and gravel deposits.

ACKNOWLEDGEMENT

This cooperative research project between the Illinois State Geological Survey (ISGS) and the Illinois Department of Transportation (IDOT) was made possible by contract funds provided by IDOT (Project IHR-416). George Dirkes, Executive Director of the Illinois Association of Aggregate Producers (IAAP) recommended that we conduct this study.

IDOT's role in this project was a major one. The test beams and expansion data from IDOT's freeze-thaw testing program, and additional information provided by William Sheftick and the staff of the Materials Testing Laboratory were vital to the study. Harold Olsen contributed data storage and statistical analysis expertise. Marvin Traylor's support and advice were essential.

ISGS laboratory research assistants were Theresa Brandabur, Doug Evans, John Fox, Sharon Geil, Kathleen Henry, Heidi Minc, and Peter Worland. Doug Evans assisted in the supervision of pebble identification work and helped prepare the final report. Staff members of the ISGS, who provided assistance during the research project, are James Baxter, Jonathan Goodwin, Joyce Frost, Dennis Kolata, and Donald Mikulic.

Statistical analysis assistance was provided by Bruce Richardson, Manager of the Mathematical and Statistical Consulting Committee, Mathematics Department, University of Illinois at Urbana-Champaign.

DISCLAIMER

INTRODUCTION

This report is the result of a cooperative research project between the Illinois State Geological Survey (ISGS) and the Illinois Department of Transportation (IDOT) as a part of IDOT's ongoing efforts to ensure the use of durable aggregate in state construction projects. The research deals with the characteristics of coarse aggregate produced from gravel deposits in and near Illinois for use in Portland cement concrete and the effects of individual rock types on IDOT freeze-thaw test results.

In Illinois, construction aggregates are produced from more than 750 sources, including sand and gravel pits, and limestone and dolomite quarries. However, prior to IDOT's implementation of freeze-thaw tests, only 70 sand and gravel pits were approved as sources of coarse aggregate for use in Portland cement concrete. In addition, 137 production ledges in 82 quarries were similarly approved, giving a total of 207 approved sources. These materials passed quality tests consisting of (1) the Na_2SO_4 Soundness test with a maximum allowable weight loss of 15 percent, (2) the Los Angeles Abrasion test with a maximum weight loss of 45 percent, and (3) a maximum deleterious materials content of 5 percent. Gravel sources were restricted to a maximum allowable total chert content of 25 percent. Gravel sources could not contain more than 4 weight percent of low specific gravity (<2.35) chert.

Despite these specifications for aggregates used in Portland cement concrete pavement, "D-cracking" had been occurring for years in Illinois highways. It was not considered a serious problem. "D-cracking" (deterioration cracking) generally refers to "fine, closely spaced cracks which occur parallel and adjacent to longitudinal and transverse joints, intermediate cracks, and the free edges of pavement slabs" (Stark, 1976). The term is also used in reference to cracks that develop in certain rock-types of coarse aggregate due to freezing and thawing. "D-cracking" begins in the coarse aggregate near the base of the pavement slab, then spreads laterally and vertically through the matrix cement. It first appears on the surface at slab corners, edges, and adjacent to joints and cracks. By 1978, several 10-year-old sections of continuously reinforced pavement in the Illinois interstate highway system had deteriorated to such an extent that complete rehabilitation was required. A statewide survey of more than 3,000 miles of pavement showed that only 42 percent of the mileage surveyed was free of "D-cracking"; 40 percent had low-level "D-cracking"; 12 percent had intermediate level "D-cracking"; and 6 percent had severe "D-cracking" (Traylor, 1982). Thus the existing quality control tests for coarse aggregate were determined to be insufficient to control "D-cracking" of Portland cement concrete pavement.

Klieger et al., (1974) demonstrated that "D-cracking" develops most rapidly where entrained air voids in the cement matrix are partially filled with water, and where the coarse aggregates are susceptible to fracturing due to frost action. They were able to isolate the coarse aggregate as being responsible for the development of this type of "D-cracking." They also demonstrated that reduction in the maximum particle-size of the coarse aggregate often can significantly reduce the effects of "D-cracking" in test beams. Stark and Klieger (1974) showed that coarse aggregates susceptible to "D-cracking" are best identified by their performance in concrete test beams subjected to cyclic freezing and thawing. Because the only known economical way to control "D-cracking" is to eliminate susceptible coarse aggregate, the

freeze-thaw test (ASTM, 1979b) was determined to be the best available method to improve IDOT's coarse aggregate quality specifications for Portland cement concrete (Traylor, 1982). Traylor (1982) described IDOT's freeze-thaw test as follows:

> By July 1979, the Illinois DOT's two new freeze-thaw cabinets were operational. They were custom built by a local manufacturer to meet ASTM C-666 requirements. Cycles are controlled by programmable modules that use a step function to approximate the desired rise and fall rates for temperature. Once programmed, all functions are completely automatic and require no operator. The modules also constantly record the temperature at several locations inside the cabinets on both circular charts and digital printout tapes.
>
> Although the equipment is sophisticated, the test is quite simple in principle. The aggregate is cast in a concrete beam that is cured, measured, subjected to a series of freeze-thaw cycles, and remeasured. A small increase in length indicates a durable aggregate, and a large increase indicates a nondurable aggregate. The following paragraphs give a general description of the test procedures. The actual test specifications can be obtained from the author.
>
> A sample of the aggregate is obtained from stockpiles at the source, separated over a nest of sieves, and recombined to a standard laboratory gradation. It is then batched, using a standard cement, sand, and air-entraining agent. The resulting concrete is formed into three 3x4x15-inch beams, cured for two weeks, brought to 73°F, and measured to establish initial lengths.
>
> The beams are placed in the freeze-thaw cabinets and exposed to eight freeze-thaw cycles (0° to 40°F) each day. Water covers the beams during the thawing phase but is evacuated during the freezing phase of each cycle. The actual cycle is shown in figure 1 (also fig. 1, this report). A complete test consists of 350 freeze-thaw cycles.
>
> Periodically, the beams are removed from the cabinets, warmed to 73°F, and measured. After each measurement, the length change, expressed as a percentage of the original length, is calculated and plotted. Total time for the test, including the 14 days for curing, is approximately nine weeks. Figure 2 (also fig. 2, this report) shows the test results for two sources. Group 1, with the lower expansions, is superior to group 2."

IDOT has freeze-thaw tested all sources of coarse aggregate previously approved for use in Portland cement concrete pavements. IDOT freeze-thaw tests of three replicate beams containing crushed limestone and dolomite from the same stone quarry showed similar percentages of expansion in all three beams. For example, tests on triplicate beams of a low-expansion crushed stone sample yielded similar results (fig. 2, group 1). The same uniformity was obtained by IDOT with tests on triplicate beams of a high-expansion crushed stone sample (fig. 2, group 2). IDOT found that reduction in the maximum size of the crushed stone particles resulted in decreased freeze-thaw

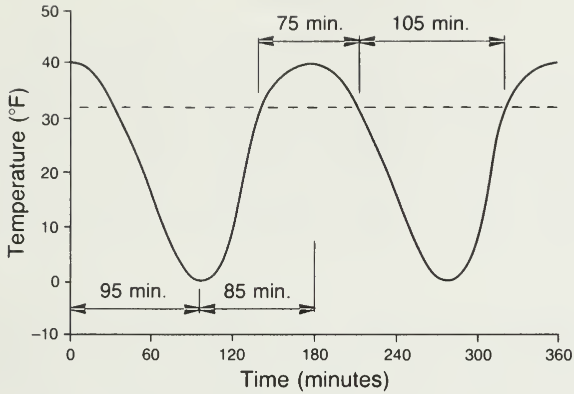


Figure 1. Temperature variations with time during freeze-thaw test cycles (Traylor, 1982).

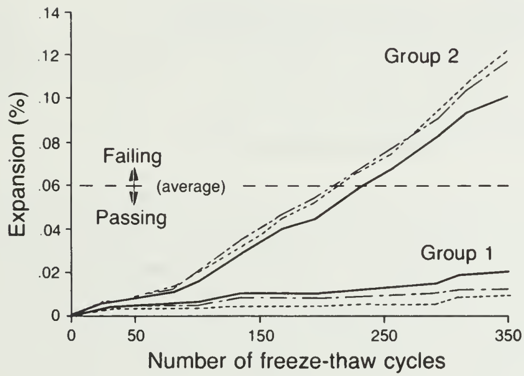


Figure 2. Typical uniform freeze-thaw test results of crushed stone samples. Expansion curves of individual test beams within two groups of three replicate beams (Traylor, 1982).

expansion, and that freeze-thaw test results on crushed stone samples correlated very well with field performance.

In contast to the uniformity of IDOT freeze-thaw test data on the crushed stone sources, test data on replicate test beams containing gravel from the same source (fig. 3) showed considerable variability among the three test beams. Results of repeated tests of gravel from the same source were also variable, and it was difficult to correlate the results of tests with field performance. Reduction in maximum size of the gravel did not always reduce expansion values. Expansion of a single piece of chert or ironstone sometimes caused one gravel beam to break (fig. 4), while the other two beams in the set had only moderate expansion. These inconsistencies reflect the variability within the gravel deposits, and the difficulty of obtaining representative samples.

In July 1981, IDOT issued an interim specification adding the freeze-thaw test to the existing quality tests. Aggregate from each source was tested in 1 1/2-, 1-, and 3/4-inch nominal top-size gradations and the largest size passing the freeze-thaw test was approved for use. If the aggregate failed to pass at the 3/4-inch nominal top size, its use in Portland cement concrete pavement was prohibited. The results of this testing on Illinois sources of aggregate for highway construction and maintenance projects are shown in table 1.

Table 1. Net effects of freeze-thaw testing three nominal top-size gradations of concrete-quality aggregate.

Types of Aggregate	Number of Aggregate Samples Being Tested: Nominal Top Size (inches) Passed: 1 1/2	1	3/4	Rejected	Total Tested
Crushed stone	65	9	4	4	82
Gravel	12	11	27	20	70

Figures 5 and 6 show the geographic distribution of crushed stone and gravel producers included in table 1, and the effect of the new freeze-thaw specification on each group of producers. Only four crushed stone sources (5 %) were rejected, and although competition may have been reduced locally, the statewide distribution of available sources of crushed stone for concrete was essentially unaffected. In contrast, 20 gravel sources (29 %) were rejected, greatly reducing competition and altering the statewide distribution of gravel for concrete. The rejection of so many gravel sources eliminated practically all local sources in some areas. For example, in the central Illinois (Springfield-Peoria) region, gravel pits were the only local source of concrete-quality aggregate, and most of them were disqualified, forcing aggregate to be transported greater distances. As haul distances increase, the delivered price of aggregate increases substantially, and the effect is to significantly increase the cost of construction projects. For example, at a

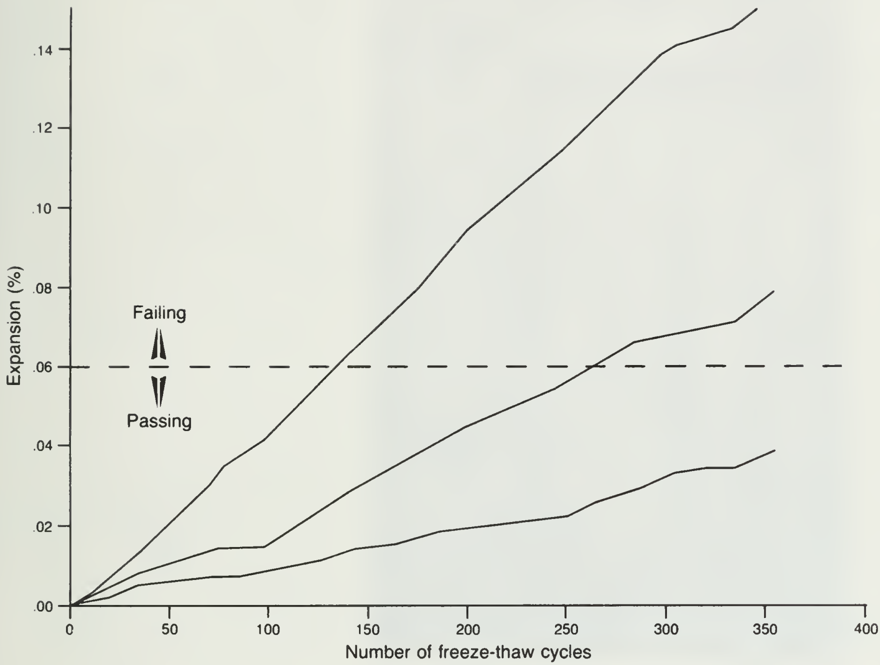


Figure 3. Non-uniform expansion curves from the freeze-thaw testing of three replicate beams from gravel sample number 11.

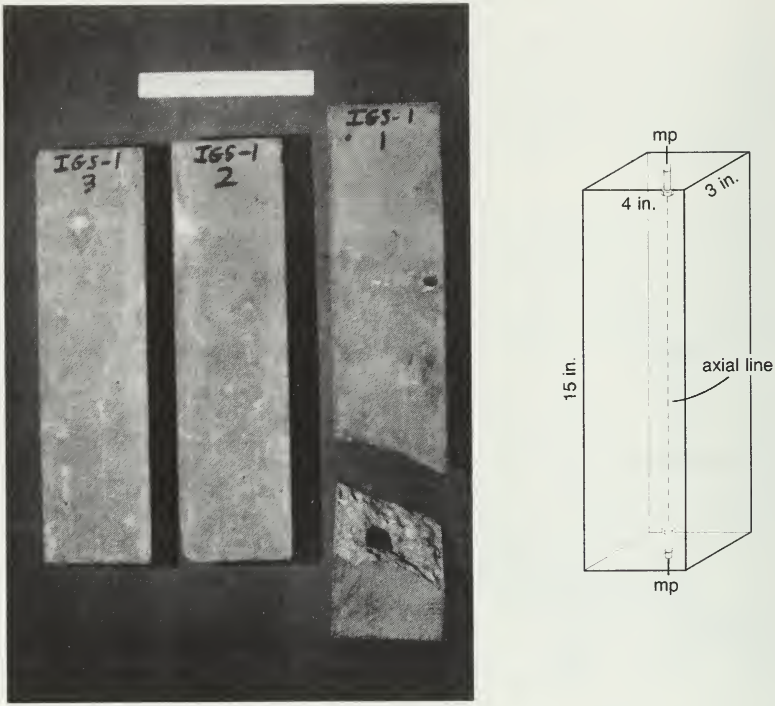


Figure 4. A triplicate set of IDOT freeze-thaw test beams (3x4x15 inches) from sample 1. Beam 1 was broken by the expansion of a large ironstone pebble lying near its axial line (see sketch). The sketch shows the orthorhombic shape of a test beam with measuring pins protruding from the center of the small ends and the axial line connecting the pins.

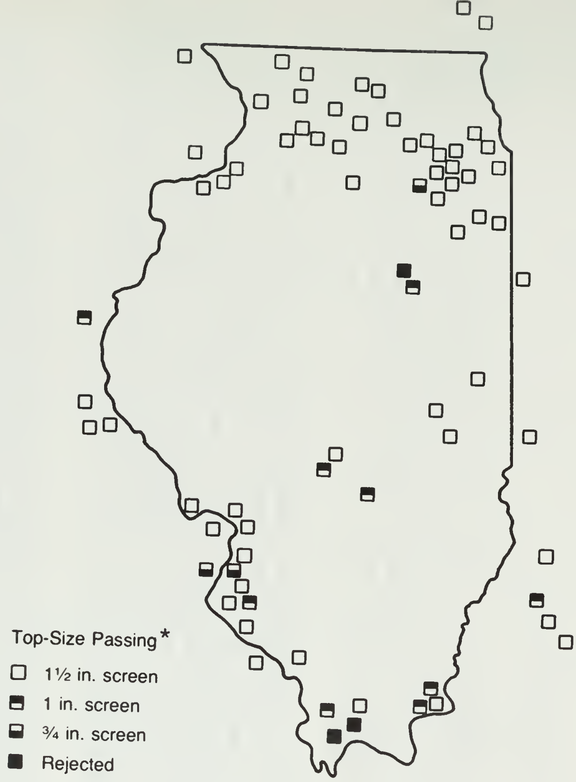


Figure 5. Effect of IDOT freeze-thaw specification on distribution of sources of concrete-quality crushed-stone in and near Illinois (Traylor, 1982).

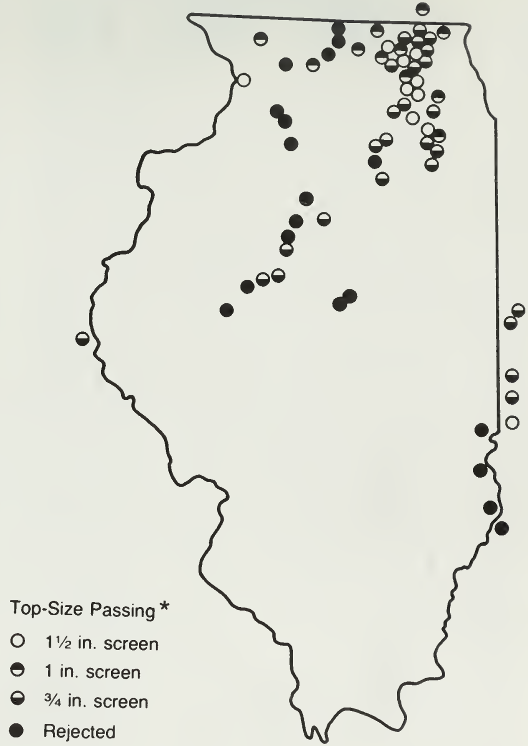


Figure 6. Effect of IDOT freeze-thaw specification on distribution of sources of concrete-quality gravel in and near Illinois (Traylor, 1982).

* "Top-size passing" indicates nominal top-size of aggregate passing specification.

distance of 50 miles from a quarry, the price of crushed stone could be three times the cost at the quarry (Subhash B. Bhagwat, ISGS, personal communication, February, 1987).

In summary, the elimination of sources of crushed stone identified as susceptible to "D-cracking" by failing the freeze-thaw test has had little effect on the availability of concrete-quality aggregates in Illinois. On the other hand elimination of the large number of gravel sources failing the test has had a significant effect on the availability of concrete-quality aggregate in Illinois. Also for individual gravel sources the variability of freeze-thaw test results was difficult to interpret, and difficult to correlate with field performance. As a result, George Dirkes, Executive Director of the Illinois Association of Aggregate Producers (IAAP), suggested that IDOT and ISGS conduct research on the freeze-thaw testing of gravels. The primary goal of this project was to identify the rock types in gravel that are susceptible to freeze-thaw expansion. This information will be used to interpret possible explanations for the variability of test results on gravel samples. The identification of problem-causing rock types will assist IDOT in eliminating the use of "D-cracking" aggregates in Portland cement concrete highways. Knowledge of these rock types may allow gravel producers to develop processing techniques that will remove deleterious types of particles from their products. Possible techniques include reduction of the maximum particle size, and the use of heavy media separation, new crushing processes, attrition and washing processes, and chemical additives.

OVERVIEW OF THE INVESTIGATION

Fifteen sources of concrete-quality gravel were selected, using available information and test data, to provide as wide a geographic distribution and as large a range of freeze-thaw test results as possible. Three sources were selected from each of the four largest production areas, and three sources from two smaller production areas. Also, two samples representing two different crushing methods, were collected from one gravel source, giving a total of 16 study samples.

In Phase I of the study, the 16 samples were collected, sized, cast, and tested by IDOT in sets of three beams per sample. ISGS described the surficial deterioration features of these test beams and then cut them into slabs in order to identify the rock types and record the presence of deterioration features affecting individual pebbles. The resulting point-count data and freeze-thaw test-beam expansion data were analyzed statistically for preliminary identification of the rock types most closely related to the freeze-thaw expansions of the test beams. IDOT subjected separate splits of the study samples to other quality tests (noted in the introduction) and these data also were analyzed statistically to see how each test related to the freeze-thaw expansions of the test beams.

Phase II of the study consisted of taking new 60-pound splits of all study samples and physically sorting each pebble into one of 28 rock type categories, as described in the appendix. The weights of the pebbles of each rock type in each of the four size-fractions (as seived by IDOT) were

recorded. A second phase of freeze-thaw testing was then initiated, using individual rock types and groups of rock types in the test beams. The surficial deterioration features were described for all Phase II test beams. A study of chert pebbles exposed in popouts in the test beams containing chert showed that three varieties of chert could be recognized and an attempt was made to evaluate differences in their durability. The resulting weight percent data and freeze-thaw test-beam expansion data were analyzed statistically to evaluate preliminary conclusions from Phase I and further identify rock types most responsible for freeze-thaw expansion. Finally, some of the factors outlined in this report are discussed in terms of the physical test data available in two gravel-producing areas where variability of test data has been a problem.

GEOLOGIC FACTORS RELATED TO THE SELECTION OF STUDY SAMPLES

Introduction

Gravel deposits that yield coarse aggregates for use in concrete are predominantly located in the northern half of Illinois and in the Wabash and Mississippi River valleys (fig. 6). In order to select study samples that are as representative as possible, we reviewed the geology of the gravel deposits and the freeze-thaw results from each source.

Gravel deposits that have historically been sources of concrete-quality coarse aggregate used in Illinois are all of glacial origin. A comparison of the locations of these gravel sources (fig. 6) with a simplified geologic map of surficial materials (fig. 7) indicates that they are located within the map unit labeled Holocene and Wisconsinan. This map unit includes the geologic materials unit named the Henry Formation, which was deposited during the youngest glacial age (Wisconsinan); all concrete-quality coarse aggregates now mined in Illinois are from this formation. A few older gravel deposits may directly underlie Wisconsinan age sand and gravel deposits. All of these deposits consist of sands and gravels that were scoured by great lobes of continental ice from pre-existing surficial deposits of variously weathered materials and from freshly exposed bedrock units. These materials were carried, shoved, and washed southward from nearby sites and from areas as far away as central Canada.

The glacial deposits in Illinois originated during three or more major advances of continental glaciers (fig. 7). As the oldest (Kansan or other pre-Illinoian) glaciers (fig. 8; nos. 1 and 3) moved into Illinois, they scoured up vast amounts of deeply weathered material and various types of fresh rock as they advanced and deposited them as far south as St. Louis. The next glaciation (Illinoian) penetrated deep into southern Illinois almost to the Shawnee Hills (fig. 8; nos. 5, 6, and 7), incorporating material from older glacial deposits along with many deleterious rock types such as coal, shale, ironstone concretions, sandstone, and siltstone as the ice lobe moved over the Illinois Basin Coal Field.

The youngest glaciation (Wisconsinan) reached only into central Illinois (fig. 8; nos. 9, 10, and 11), again incorporating materials from older glacial deposits as well as the exhumed portions of bedrock units it scoured across. The gravel deposits associated with each of these glaciations contain rock and

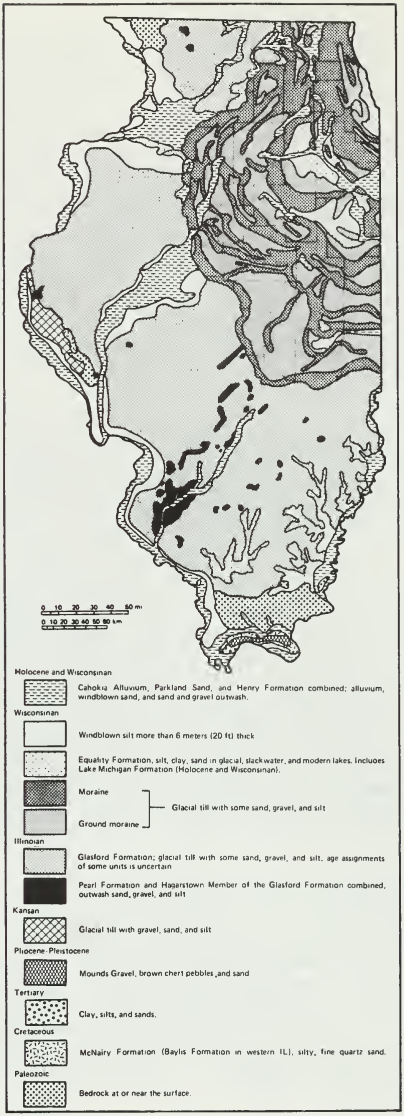


Figure 7. Simplified geologic map of surficial unconsolidated materials (Quaternary and older) in Illinois (after Lineback, 1979 and 1981).

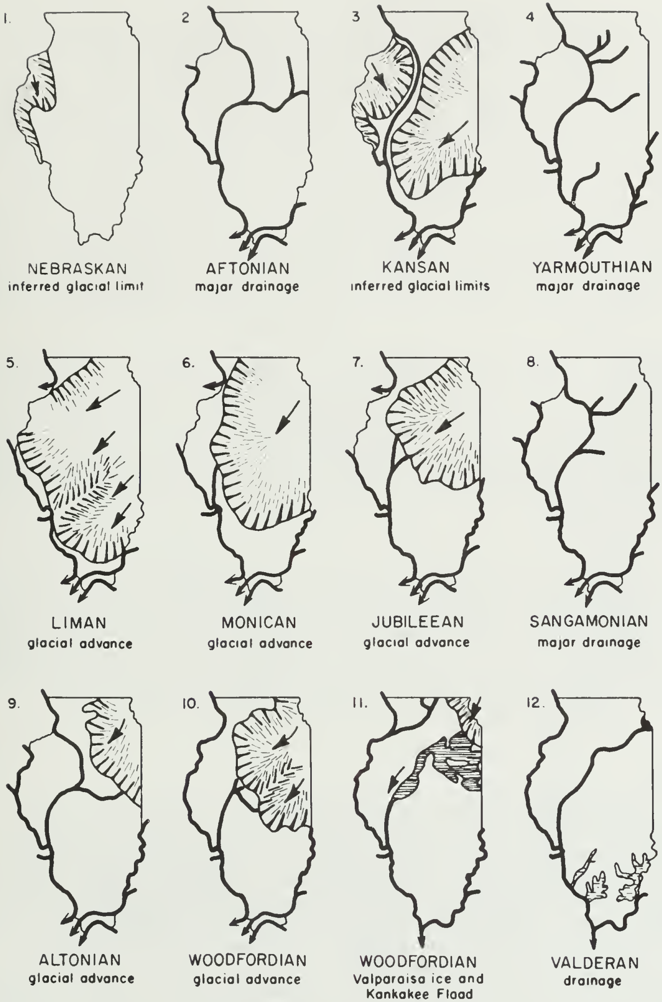


Figure 8. Sequence of maximum glacial and major interglacial drainages in Illinois from Willman and Frye (1970); pre-Illinoian: 1 through 4; Illinoian: 5 through 8; and Wisconsinan: 9 through 12.

mineral types that are characteristic of bedrock strata the ice lobes crossed, plus a mixture of materials picked up from older glacial deposits.

Deposits of the youngest of the Wisconsinan glacial lobes, which reached only into northeastern Illinois, consist almost entirely of unweathered material from bedrock units in northeastern Illinois, Wisconsin, Michigan, and Canada. Older Wisconsinan glacial lobes reached farther south into Illinois; in general, they contain more material incorporated from previous glacial deposits than did the younger lobes, as well as rocks and minerals scoured from additional bedrock units as the ice lobes moved southward. Therefore, gravel deposits in northern (especially northeastern) Illinois contain the greatest amounts of unweathered, durable rock and mineral types, mainly dolomite and small amounts of various igneous and metamorphic rocks (Masters, 1983, Table 1). Older gravels located progressively farther south tend to contain greater amounts of weathered material and deleterious rock types, such as chert, sandstone, siltstone, shale, ironstone concretions, coal, and wood. The older gravel deposits also have, in general, experienced deeper weathering in place.

The amount of high-quality gravel in a deposit may also be related to its mode of deposition. The highest energy modes of deposition generally result in the highest quality gravel; that is, outwash plains and fans often contain more high-quality gravel than do kames, eskers, or valley trains. Another reason for the durable gravel in northeastern Illinois is that Wisconsinan glacial activity eroded away much of the older glacial deposits and then laid down the most extensive and coarsest-grained outwash-plain deposits in the state (Masters, 1978).

In order for the study samples to be as representative as possible, it was necessary that sources from as many separate gravel deposits as possible be included. The study samples were also obtained from widely spaced geographic locations in order to represent the differences in composition related to different source areas and local geology. As sources were being selected, previous freeze-thaw test results were considered in order to ensure that products with a wide range of test results would be included.

Sampling sites

Fifteen sources were chosen to provide samples from outwash-plain deposits in northeastern Illinois and valley-train deposits in the Rock, Fox, Illinois, Kickapoo, and Wabash River valleys (fig. 9). All samples were collected from production stockpiles containing nominal 3/4-inch top-size gravel. Two samples were obtained from source no. 5, for a total of 16 study samples; these samples (5a and 5b) had been specially prepared to determine if the physical properties of gravel produced with two different types of crushers are significantly different (see section on applications of rock-type data). Sample 5a had been processed with a combined jaw and roll crusher unit, and sample 5b had been processed with a vertical impact crusher; both had been completely reduced to pass through a 3/4-inch square apperture seive. The sample from the Mississippi River valley source was analysed only petrographically, and was not considered in the freeze-thaw evaluation.

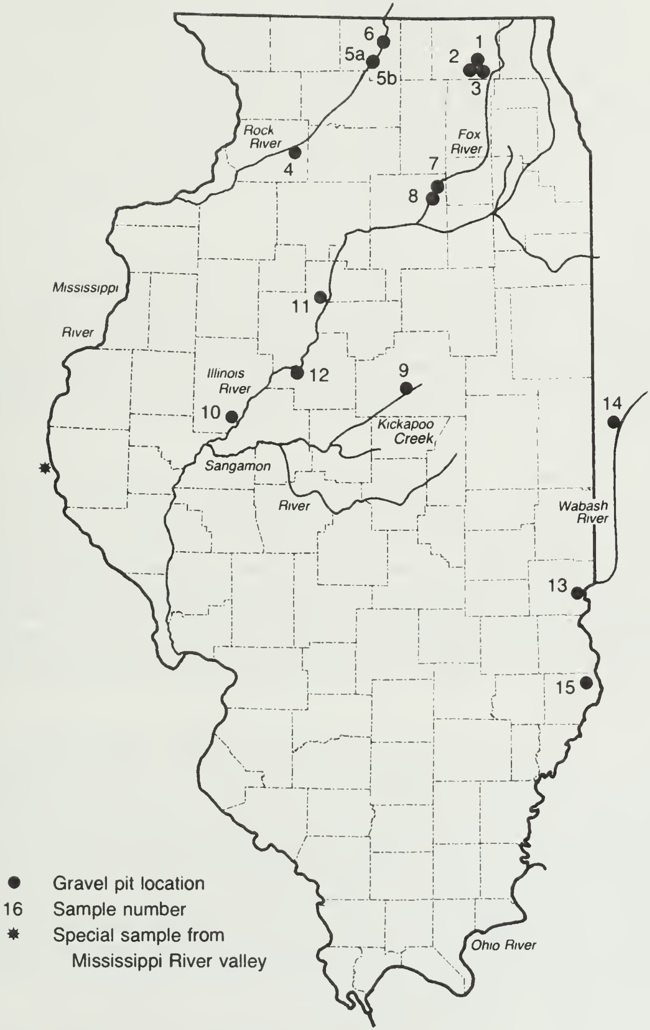


Figure 9. Locations of gravel pits from which processed samples were obtained for this study.

Samples 1, 2, and 3 are from sand and gravel pits in Wisconsinan age outwash plains (figs. 7 and 9) in McHenry County. Geomorphically, these outwash plains are in the form of a slightly hummocky upland. The gravel deposits are very coarse grained and locally contain abundant boulders. The gravel was deposited from very high-velocity meltwater torrents, very close to the glacial ice margin. Most of the gravel is locally derived from dolomite bedrock along the west and southwest margin of the Lake Michigan Basin. In the three pits sampled, material is excavated from above and below the water table, however, because there is an upward coarsening of material throughout the area, most of the gravel is excavated from above the water table.

All other samples were produced from Wisconsinan-age valley-train deposits that were selected to be as widely separated from each other as possible. Although these samples were expected to contain relatively similar suites of rock types, their source areas were sufficiently different that the amounts and characteristics of many rock types were also expected to differ significantly. All of these sand and gravel pits are located in terrace deposits that topographically are relatively low and have nearly flat surfaces. The elevation of these terrace surfaces above the associated rivers varies from about 0 to 60 feet, depending on the respective river valley and its complex of terrace systems.

Samples 7 and 8 are from sand and gravel pits located in Wisconsinan-age valley-train deposits in the Fox River valley (figs. 7 and 9) in La Salle County. Both pits are developed in terrace deposits about 15 to 20 feet above the Fox River. These deposits contain material that was derived from areas similar to the source areas of the McHenry County outwash plain gravels (samples 1, 2, and 3); however, these terrace gravels were derived from a larger source area and were washed down the Fox River valley and deposited by lower energy meltwater streams farther from the glacial front than were the McHenry County gravels. Sample 7 included material produced from both above and below the water table, while sample 8 was from material produced only above the water table.

Samples 4, 5a, 5b, and 6 are from sand and gravel pits in the Wisconsinan-age valley-train deposits in the Rock River valley (figs. 7 and 9). Samples 5a, 5b, and 6 are from pits in a "high terrace" 40-50 feet above the river; sample 4 is from a pit in a "low terrace" 20-30 feet above the river (Anderson, 1967). Samples 5a, 5b, and 6 were collected from material excavated from above the water table, and sample 4 was collected from material above and below the water table at a location much farther downstream than the others. Sample 4 was expected to be different from samples 5a, 5b, and 6, not only because of its downstream position, but also because it was apparently from a different terrace system. The fact that some material in sample 4 is from below the water table is probably less significant than the fact that it was from a differenct terrace system.

Samples 10, 11, and 12 are from sand and gravel pits in the Wisconsinan-age valley-train deposits in the Illinois River valley (figs. 7 and 9). Sand and gravel deposits vary considerably both with distance down the Illinois River valley and with depth below the surface (Willman, 1973). Sample 11, collected at the most upstream location, is from a "gravelly high terrace" deposit about 50-75 feet above the river. The next sample downstream, 12, is from a "sandy high terrace" deposit about 50-75 feet above the river. Sample

10, from farthest downstream, was obtained from a "sandy low terrace" deposit about 5-15 feet above the river. These three samples are from deposits sufficiently different in physical characteristics to suggest that each one could be from a different terrace system. However, the upstream (11) and intermediate (12) samples may be from the same terrace system, reflecting a decrease in the coarseness and abundance of its gravel toward the downstream location. Sample 11 was produced from an interval ranging from 25 feet above to 25 feet below water; sample 12 was produced from a dry pit with a face 45 feet high. Sample 10 is probably from a different terrace system; material included in sample 10 that was excavated more than 20-30 feet below the water table is probably part of still another, much older valley-train deposit (Illinoian age).

Sample 9, from a sand and gravel pit in the Kickapoo Creek valley in McLean County, Illinois (figs. 7 and 9), contains material excavated from about 2 feet above the water table to 20-30 feet below it. The Kickapoo Creek terrace system, a Wisconsinan-age, low terrace valley-train deposit, is one of the coarsest grained, best-washed sand and gravel deposit in Illinois that is not associated with a modern major river valley.

Samples 13, 14, and 15 are from sand and gravel pits in Wisconsinan valley-train deposits in the Wabash River valley (figs. 7 and 9). These deposits form a complex of terrace systems similar to those terrace systems in the Illinois River valley, but little information is available on these systems. Sample 14, from the most upstream location, contains material excavated from a high terrace. The working face of the pit extends from 35-45 feet above the water table to about 10 feet below. Sample 13, from the intermediate location, was excavated from a face that extends from 25 feet above the water table to 57 feet below. Sample 15, from farthest downstream, contains low terrace material dredged from 20-25 feet below the water table. Of these three sources, only sample 14 is from a deposit that contains an abundance of medium to coarse gravel.

CLASSIFICATION OF ROCK TYPES

Introduction

The classification scheme used to identify the various constituents of the gravel samples in both Phase I and Phase II was designed to (1) make allowances for the possibility that certain rock types or physical properties of gravel may be more important than others in causing deleterious behavior of aggregate in Portland cement concrete, and to (2) demonstrate the variability in rock-type composition of gravel deposits. The descriptions of the rock types given in the appendix are based on commonly used rock and mineral names, and textural and compositional terminology (Bates and Jackson, 1980; Pettijohn, 1957; Moorhouse, 1959; and Pirsson and Knopf, 1947); but do not include highly technical terminology. The rock types are differentiated on the basis of features that generally are visible under a 10-power hand lens (fig. 10), although a low-power binocular microscope is often helpful. For convienience the microscope was always used for identifying pebbles on slabs cut from test beams (fig. 11). A modified ice pick to test hardness, a 10-percent solution of hydrochloric acid, and a bright light also were used to differentiate rock types.

Figure 10. Combination hand lens (a) and hardness tester (b).

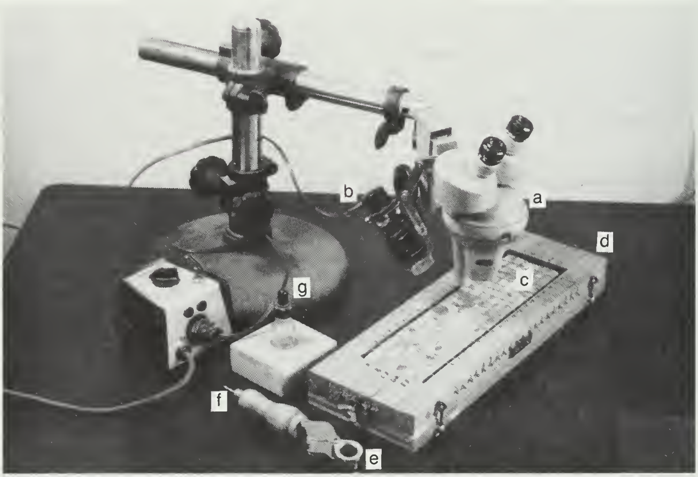


Figure 11. Binocular microscope (a) and light (b), shown along with a slab cut from a test beam (c), in the point-counting box (d), the combination hand lens (e), and hardness tester (f), and an acid bottle in a holder (g).

Many rock types were classified by use of specific rock names, such as dolomite and limestone, or rock names coupled with modifiers, as in laminated dolomite. Classification of others involved the recognition of certain groups of rocks with similar compositions or genesis. To classify the compositions of the study samples, we used specific sedimentary rock names and subdivided dolomite into four categories, because of the abundance and variety of dolomite pebbles in our samples. But we lumped most metamorphic and igneous rocks in broad genetic groups, such as metasediments and mafic rocks because they were not abundant.

The dolomite subtypes were based on the presence of textures and mineral contents that might be related to freeze-thaw expansion. We established a sequential ordering of dolomite categories: (1) dolomite (appendix, photo 1) relatively pure and non-friable; (2) laminated dolomite (appendix, photo 2), having visible layering of different types; (3) silty dolomite (appendix, photo 3), similar to the first two subtypes, but permeable and containing silt, sand, or clay; and (4) pyritic dolomite (appendix, photo 4), similar to any of the other three but containing particles of pyrite.

Because of the relatively small amounts of metamorphic and igneous rocks in the samples, group names were used as rock types. For instance, within the spectrum of metasedimentary rocks, many pebbles could be given specific rock-type names based on their texture and mineralogy, but we did this only if these pebbles were abundant in our samples (e.g., quartzite, photo 28). The textural and mineralogical differences between metasediments, metagraywackes, and tillites are not obvious in the photos (appendix, photos 24, 26, and 27), but when we used a hand lens, the differences became distinct. They were easily identified under the binocular microscope in the slabs cut from the test beams. Such distinctions can be very important in the evaluation of freeze-thaw expansion; other studies have found that specific rocks such as metagraywackes cause significant expansion (Stark, 1976).

Several tests are used to differentiate rock types. In the dilute HCl test as referred to in the rock type descriptions (appendix), the acid is applied from a dropper bottle to the surface of a pebble (fig. 12). Pebbles classified as limestone give a vigorous effervescence when tested with dilute HCl. The scratch test to determine hardness involves holding the pebbles and scratching their surfaces with a blunt steel tool (figs. 10 and 11). The 10-power hand lens (15-mm diameter) was attached to the hardness tester to save time. The ease with which pebbles scratch is a reflection of both mineralogical composition and weathering. The hardness tester will powder minerals that are softer than steel, whereas minerals harder than steel will remove metal from the tool. Highly weathered minerals and highly porous rock types (e.g., porous, chalky chert) may be scratchable or gougable even though they normally are harder than steel.

Identification of rocks depends on the recognition of distinctive physical properties. Although some rock types are often very unique, the physical characteristics of one rock type sometimes grade into the physical characteristics of another, and the boundary between them depends on some defined limit. For example, in the classification of igneous rocks, a granite and a felsite may have the same mineral and chemical compositions, but by definition are differentiated on the basis of grain-size. Thus, in granites many mineral grains can be identified by the unaided eye, whereas in felsites they cannot.

Figure 12. Dropper bottle containing dilute hydrochloric acid, suspended on a stand so that acid may be applied to a pebble by touching it to the nipple.

We have used the general terms "coarse felsite" and "fine felsite" to encompass all silica- to alumina-rich igneous rocks of granitic to syenitic composition.

Basically, rocks are divided into three major classes: sedimentary, igneous, and metamorphic. This classification depends on the recognition of certain physical properties that are associated with their modes of origin. Sedimentary rocks consist of fragmental or chemical particles that accumulated in layers and were then consolidated. These particles are in contact with each other, but not interlocking. Igneous rocks consist of material that has solidified from a molten or partly molten state. This material is usually crystallized into a variety of characteristic minerals, such as feldspar. The interlocking texture of these minerals is characteristic of this class. Metamorphic rocks are derived from any pre-existing rock that has undergone mineralogical, chemical and/or structural changes, essentially in the solid state. These rocks contain evidence of having been subjected to various dynamic forces deep in the Earth's crust, such as disruption of interlocking minerals or their re-crystallization and alignment into bands of individual minerals, all oriented in the same direction.

Sedimentary rocks

Pebbles of sedimentary rocks in our samples are predominantly well-to-moderately consolidated dolomites, cherts, and limestones, plus less abundant and generally less well-consolidated clastic rocks, such as sandstone-siltstone, and shale. All are derived from nearby bedrock units. In general, these sedimentary rocks in Illinois were originally deposited in ancient seas or near-sea swamps and rivers, roughly 300 million to 600 million years ago during the Paleozoic Era.

Igneous and metamorphic rocks

Pebbles of igneous and metamorphic rocks are much less abundant in our samples than are than the sedimentary rock pebbles. In general, they are much older than the sedimentary rocks--in the range of 600 million to 4.5 billion years (Archean and Proterozoic)--and come from more distant sources in the Canadian Shield. In terms of composition, texture, and structure, this group encompasses an enormous variety of individual rock types. Within the scope of this study, it was not practical to classify all these types individually, nor was it adequate to merely lump all this material into the two umbrella classes, igneous and metamorphic. Therefore, we described groups of broadly related individual rock types that represented the most abundant materials in these gravel samples, and that might be related to freeze-thaw expansion.

As previously mentioned, we had to broaden or narrow the designations of certain rock types to fit the needs of this study. For example, mafic igneous rocks were very rare in our samples, so we grouped fine- and coarse-grained mafic rock types together as a single category. However, we decided that fine- and coarse-grained felsic igneous rocks should be classified separately because of their abundance, and because of the possibility that fine felsic rocks may be deleterious in Portland cement concrete (ASTM, 1979a).

The characteristics of metamorphic rocks depend upon both the composition of the original rock and the degree of metamorphism. Gradational differences and intermediate varieties complicate the classification process. In the low-grade metamorphic rock types, especially those derived from sedimentary rocks, little or no metamorphic fabric is detectable and types are distinguished primarily on the basis of variations in composition. Such compositional distinctions may be important, since some partially metamorphosed sedimetary rocks have been associated with "D-cracking" (Stark, 1976). In general, high grade metamorphic rock types are distinguished on the basis of the coarsness of metamorphic crystals and development of mineral alignment (foliation). These features have not been related to "D-cracking" (Stark, 1976).

PHASE I: FREEZE-THAW TESTING OF PROCESSED GRAVEL SAMPLES

Experimental design

In Phase I, IDOT personnel collected approximately 500 pounds of gravel per sample from the selected sources, using their standard sampling procedure, and documented the excavation and production methods used at each gravel plant. Each sample was sieved into four size ranges. Sufficient material for a three-beam freeze-thaw test was obtained: 3 pounds of 1- to 3/4-inch material, 24 pounds of 3/4- to 1/2-inch material, 12 pounds of 1/2- to 3/8-inch material, and 21 pounds of 3/8-inch to number 4 mesh-size material, giving a total of 60 pounds of coarse aggregate to mix in the concrete batch for each test. Material from each sample was retained by IDOT in order to perform all tests they routinely make on coarse aggregates for use in Portland cement.

After the 350-cycle freeze-thaw tests were completed, the test beams were delivered to the ISGS. For each test beam the crack patterns and location of popouts on the beam surfaces were sketched, and the rock types in the popouts were identified. The beams then were sawed into slabs and the slabs prepared for the point-counting procedure. In the point-counting procedure, the rock types exposed on the slabbed surfaces were identified (see appendix), and tabulated. The number of pebbles of each rock type that were cracked were also counted. Deterioration features (cracking) in the matrix and pebbles exposed in the slabs were described and sketched. Comparisons were made between the abundance of selected rock types and the respective percentages of cracked pebbles. Statistical analyses were made of the Phase I rock type data from the point-counting method as a first attempt to establish which rock types caused expansion of the beams during the freeze-thaw tests. The results of other IDOT quality control tests on the study samples also were compared to the expansion values from the Phase I test beams.

Cracks and popouts

The beam surfaces exhibited freeze-thaw deterioration features in the form of cracks and popouts (fig. 13). A standard form (fig. 14) on which the six sides of the orthorhombic-shaped beams (fig. 4) were drawn to scale was used to sketch the cracks and popouts in each beam. Pebbles exposed in the popouts were identified by rock type (see appendix).

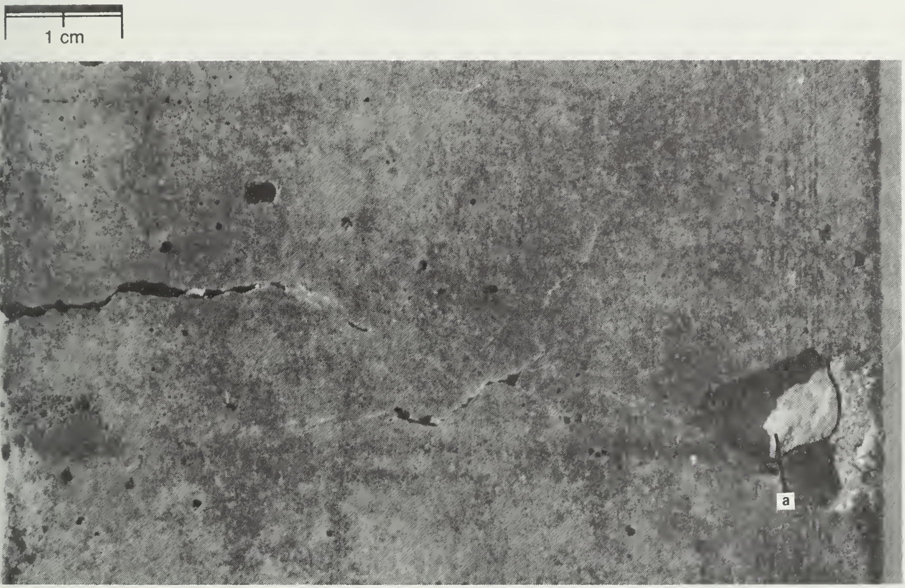
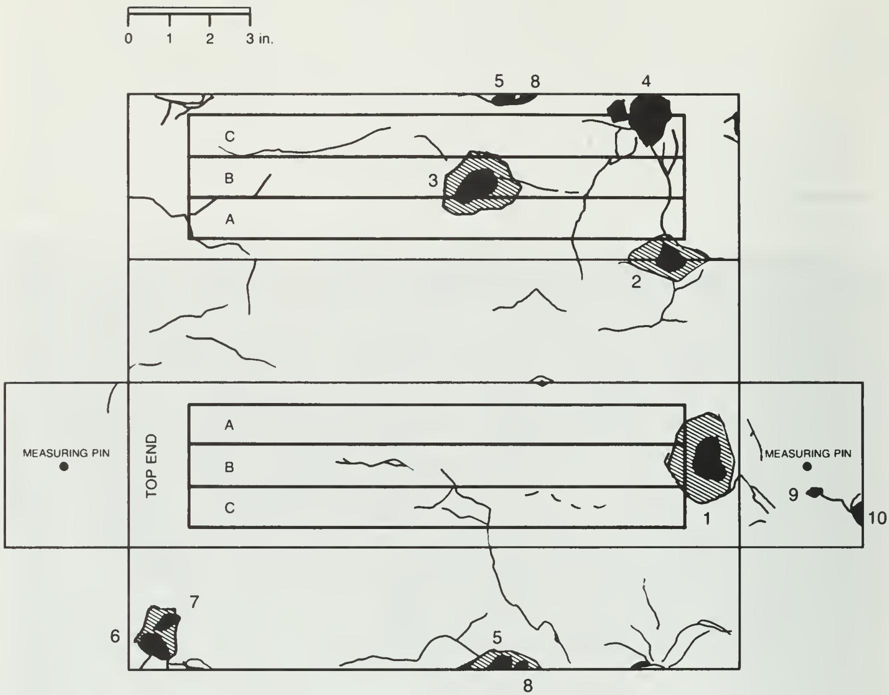


Figure 13. Deterioration features on a Phase I test beam surface. The popout surrounds a chert pebble (a), and is connected to a network of cracks that cross the three-inch wide side of the beam.



Types of Pebbles
in Popouts:

1	Chert	6	Chert
2	Chert	7	Chert
3	Ironstone	8	Chert
4	Chert	9	Chert
5	Chert	10	Chert

Figure 14. Standardized two dimentional layout of surfaces of a test beam (see three-dimentional sketch on fig. 4), illustrating surficial deterioration features and how they were recorded.

Table 2 contains the data on average expansion and number of pebbles in popouts. It reveals that only 6 of the total 28 rock types were found in popouts, and that chert pebbles were the most abundant, followed by ironstones and weathered carbonates. The graph of the total numbers of pebbles in popouts plotted against the average expansion values for the Phase I test beams looks scattered (fig. 15), and a simple regression analysis indicates there is not a significant relationship. Therefore, surficial deterioration features do not appear to be a sensitive indicator of expansion for the Phase I beams. Examination of slab surfaces cut out of the test beams indicates that the most critical factor in determining whether or not a susceptible pebble will cause a popout is its proximity to the surface of the beam.

Slab preparation and point counting

Point counts of the rock types were made on slabs sawed from Phase I test beams. Each beam was systematically sawed into slabs A, B, and C, using diamond-blade rock saws (fig. 16). All four of the 3- by 12-inch faces on slabs A and C were ground smooth with 80- and then 400-grit grinding powder on a vibrating table (fig. 17). One hundred identifications were tabulated on every prepared face, each point being defined by an evenly spaced wire grid (fig. 18). Approximately 55 percent of the points fell on coarse aggregate particles; 45 percent on cement matrix, including bubbles and particles smaller than 1/8-inch. On the average, 220 rock-type identifications per beam (660 per three-beam sample set) were made. Deterioration features such as cracks in pebbles and matrix material were recorded. Practically no reaction rims were found; reaction rims are evidence of a chemical reaction between the aggregate and the cement (Dolar-Mautuani, 1983). Rock-type identifications and other observations were made with a binocular microscope (fig. 11) of low magnification.

Rock type and cracked pebble data

The average percentage of each rock type found in each sample by the point-count method and the average expansion value for each sample are given in table 3. Tables 4, 5, and 6 give the rock type data and expansion values (highest, intermediate, and lowest) obtained from each of the three replicate beams tested per sample.

These data are an indication of the range of rock type variability in the samples. For example, the point-count percentage of chert in each of the triplicate test beams often varies widely. In sample 6, the chert contents of 27.9, 24.6, and 18.7 percent vary directly with expansion; however, this relationship is not consistent. For sample 10, just the reverse is true; the highest chert content (27.5%) is in the lowest expansion (0.035%) beam and the lowest chert content (24.8%) is in the highest expansion (0.082%) beam (tables 4, 5, and 6). The average chert percentage found in samples from within the same production area are also variable, and chert percentages vary the most (16.0% to 24.5%) in the Illinois River valley (table 3, samples 10 and 11). Between production areas, chert percentages range from 6.3 percent in the McHenry County outwash plains to 24.9 percent in the Wabash River valley trains (table 3, samples 2 and 15).

Table 2. Number of pebbles found in popouts in the triplicate sets of test beams and average freeze-thaw expansion of each set (Phase I).

	Sample number															
	1*	2	3	4	5a	5b	6	7	8*	9	10	11	12	13	14	15
Average Expansion (%)	.028	.016	.030	.081	.059	.041	.062	.062	.030	.067	.063	.089	.082	.067	.066	.063
Pebbles classified by rock types found in popouts (counts)																
Chert		9	10	21	13	9	13	13		15	15	8	14	14	14	14
Dolomite		0	0	0	0	0	4	0		1	0	0	0	0	0	0
Cherty dolomite		0	0	0	0	0	0	1		1	0	0	0	0	0	2
Ironstone		7	4	1	0	0	0	1		14	6	8	13	3	4	4
Silty dolomite		2	1	0	0	0	2	3		0	0	0	4	0	3	0
Weathered carbonate		2	5	3	1	0	0	1		9	2	2	4	1	1	0
Total Pebbles in Popouts		20	20	25	14	9	19	19		40	23	18	35	18	22	20

* No data are available on pebbles in popouts for samples 1 or 8.

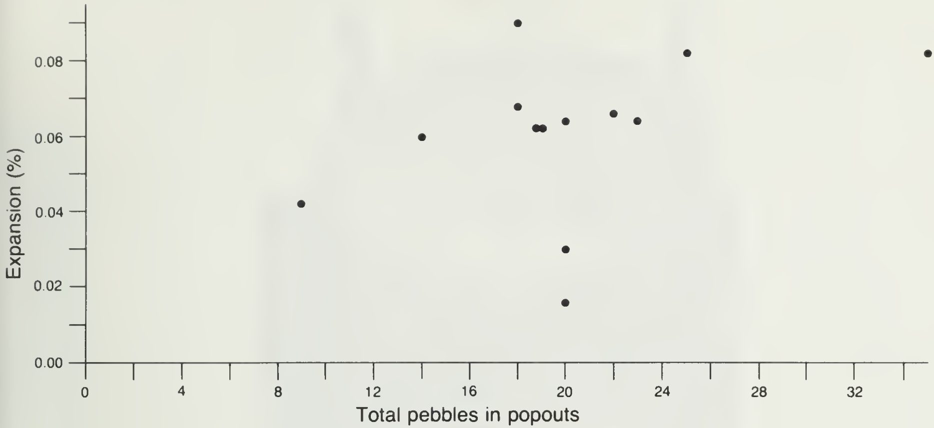


Figure 15. Total number of pebbles in popouts compared to average expansion of 14 triplicate sets of Phase I (point count) freeze-thaw test beams. Statistical values of the simple linear regression with degrees of freedom of 1 and 12 are: R-Square = 0.13, F Value = 1.76, and Prob > F = 0.2088.

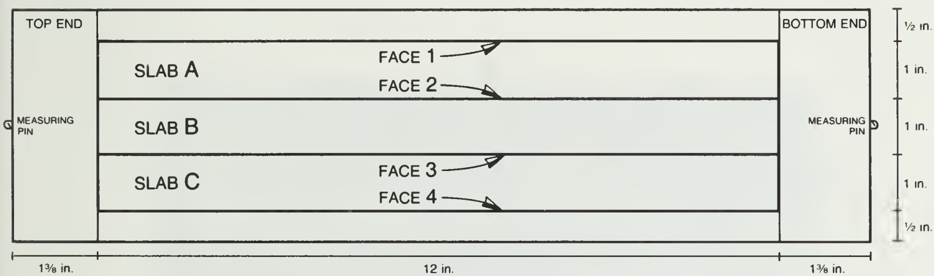


Figure 16. Diagram of the top surface of a freeze-thaw test beam with measurements and lines for rock-saw cuts. Letters A, B, and C identify slabs cut from the central portion of the beam. Both cut surfaces of slabs A and C (faces 1, 2, 3, and 4) were studied for rock-type contents and deterioration features. The measuring pins are shown protruding from the small (left and right) ends.

Figure 17. Vi-Bro-Lap used to polish slab surfaces (top is 28 inches in diameter).

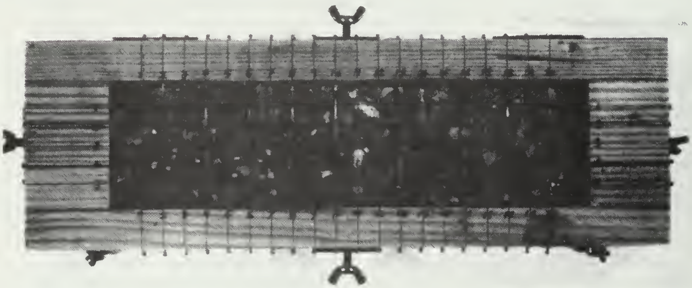


Figure 18. Point-counting box containing a polished slab (3 x 12 inches) under the point-count grid.

Table 3. Average point-count percentage of each rock type and average freeze-thaw expansion percentage in the triplicate test beams of each gravel sample (Phase I).[+]

	Sample number															
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15
Average Percent Expansion	0.028*	0.016	0.030	0.081	0.059	0.041	0.062	0.062	0.030	0.067	0.063	0.089	0.082	0.067	0.066	0.063
Sedimentary Rocks																
Oolomite	65.9	63.3	65.5	45.4	54.1	43.8	45.8	55.9	63.0	29.3	25.5	41.9	33.9	21.2	22.2	18.8
Laminated dolomite	1.1	2.7	3.3	2.5	2.7	2.6	1.7	3.1	0.7	3.0	0.6	0.9	2.0	1.1	1.7	0.3
Silty dolomite	1.1	1.0	1.2	1.5	1.3	0.2	1.0	1.9	2.0	5.2	3.0	2.2	2.3	0.9	2.4	0.3
Pyritic dolomite	1.7	0.6	0	0	0	0	0.3	0.1	1.6	0.2	0	0	0	0	0	0
Limestone	3.2	4.4	3.9	4.9	1.8	3.4	2.8	3.9	3.1	11.4	9.6	7.4	8.1	10.5	11.8	7.5
Cherty carbonate	4.6	4.9	1.6	2.9	3.2	3.5	2.9	5.5	5.1	3.7	2.6	4.5	4.4	3.1	3.8	6.3
Chert	7.2	6.3	7.7	22.0	20.3	23.8	23.6	10.2	9.8	15.4	24.5	16.0	19.2	22.4	18.0	24.9
Weathered carbonate	5.0	3.8	3.7	3.6	3.2	4.0	3.4	7.4	4.7	14.1	2.7	4.8	5.7	5.4	2.8	5.4
Ironstone	0.3	0.2	0.4	0	0.3	0	0	0	0.1	0.6	0	1.0	0.8	0.4	0.2	0
Shale	0	0	0	0	0	0	0	0	0	0.2	0	0.5	0.3	0.5	1.4	0
Sandstone-siltstone	1.1	1.7	1.6	3.7	2.0	3.4	2.7	1.7	1.3	4.6	2.4	5.5	3.7	4.2	4.7	9.0
Igneous Rocks																
Mafic	2.1	2.7	2.7	1.2	1.2	3.2	1.8	1.7	2.1	0.9	2.0	2.4	1.5	2.9	10.1	3.1
Weathered mafic	0.6	0.2	0	0.3	0.2	0.3	0.6	0.3	0.3	0	0.2	0.3	0.7	0.5	1.4	1.0
Coarse felsic	0.3	0.3	0	0.2	0	0	2.4	0	0.4	0	4.5	0.2	0.2	0.9	0.4	0.6
Weathered coarse felsic	0	0	0.2	0	0.2	0	0	0	0	0	0	0	0	0	0	0.2
Fine felsic	0.3	0.2	0.7	0.3	0	0.5	0.4	0	0.1	0.2	2.3	1.4	1.5	0	0	0.5
Massive quartz	0	0.5	0.6	1.0	1.0	0.2	2.1	0.9	0.3	2.5	3.9	1.2	1.3	2.5	1.7	3.6
Metamorphic Rocks																
Gneissic	2.3	3.0	3.0	3.2	3.8	3.7	2.7	2.6	4.1	2.1	3.6	3.3	4.1	3.4	4.7	5.2
Weathered gneissic	0.5	0.2	0.3	0	0	0	0	0	0	0.2	0.8	0.2	0.2	0.5	0	0.5
Schistose	0.5	0	0	0	0	0.5	0	0	0.3	0.2	0.2	0	0	0.2	0.2	0.6
Weathered schistose	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Metasedimentary	1.5	2.2	2.2	4.6	2.5	3.2	3.6	3.0	0.3	3.7	8.0	3.1	5.7	11.9	6.6	7.0
Weathered metasedimentary	0.2	0	0	0	0	0	0	0.1	0	0	0.3	0.3	0.3	0.4	0.2	0.3
Metagraywacke	0.5	1.7	1.5	2.0	2.3	3.2	2.0	0.9	0.6	1.5	2.0	2.2	2.8	2.2	0.9	2.4
Tillite	0	0.2	0	0	0.2	0.3	0.1	0.3	0	0	0	0.3	0.2	3.3	1.9	1.2
Quartzite	0.2	0	0	0.7	0	0.2	0.3	0.5	0.1	1.1	1.5	0.3	1.5	1.6	3.1	1.5

*Includes one projected expansion value, due to a broken beam.
[+]Conglomerate and weathered fine felsic rock names (appendix) are omitted from the list of rock types because none were found with this method.

Table 4. Point-count percentage of each rock type in test beams with highest percent expansions in each triplicate set of beams (Phase I).

	Sample number															
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15
Percent Expansion	0.035*	0.018	0.034	0.087	0.065	0.046	0.078	0.075	0.046	0.072	0.082	0.154	0.106	0.092	0.083	0.088
Sedimentary Rocks																
Dolomite	62.0	68.4	67.0	39.2	51.8	39.9	40.1	51.8	65.9	30.2	23.1	39.6	42.6	18.6	24.2	19.9
Laminated dolomite	3.3	2.9	2.8	3.6	3.6	4.0	2.7	2.8	0.9	1.4	0	1.0	0.5	2.7	0	0
Silty dolomite	1.4	1.5	0.9	3.1	0.5	0	0	1.2	1.8	4.5	5.1	3.1	1.1	2.2	3.4	0
Pyritic dolomite	2.8	1.0	0	0	0	0	0.5	0	0.4	0	0	0	0	0	0	0
Limestone	4.2	2.9	5.7	6.2	2.5	5.1	3.6	5.9	3.1	12.6	11.1	8.6	7.4	7.1	13.5	6.3
Cherty carbonate	4.7	2.9	2.8	2.1	2.5	3.0	3.2	6.7	3.9	4.1	3.0	3.6	2.1	4.4	3.9	6.3
Chert	6.1	4.9	6.1	23.2	20.8	20.2	27.9	12.6	10.5	16.7	24.8	16.8	16.3	27.9	16.9	27.6
Weathered carbonate	3.8	2.9	4.3	4.6	3.6	5.1	4.1	6.7	5.2	9.9	2.1	4.1	5.3	3.8	2.8	5.9
Ironstone	0.9	0	0.9	0	0	0	0	0	0.4	0.5	0	1.5	2.1	0	0	0
Shale	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	1.1	1.1	0
Sandstone-siltstone	0.9	0.5	1.4	3.6	2.0	3.5	2.3	2.0	1.3	5.0	2.6	6.6	4.7	4.4	3.9	10.0
Igneous Rocks																
Mafic	3.8	3.4	2.4	1.0	1.0	4.0	2.7	1.2	0.9	0.9	2.6	2.5	1.6	2.7	12.9	3.2
Weathered mafic	1.4	0	0	0	0	0	0.9	0.4	0	0	0	0.5	0.5	0.6	1.1	0
Coarse felsic	0.5	0	0	0	0	0	1.8	0	0.4	0	3.0	0.5	0	1.6	0	1.4
Weathered coarse felsic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fine felsic	0	0.5	0.5	0	0	0.5	0	0	0.4	0.5	2.1	0.5	2.1	0	0	0
Massive quartz	0	1.5	0	1.6	1.5	0	1.4	1.2	0.4	1.4	3.9	1.0	1.1	1.6	0	5.4
Metamorphic Rocks																
Gneissic	0.5	2.9	2.4	2.6	3.6	5.6	4.1	4.0	3.1	3.6	3.9	2.5	4.2	3.3	2.8	5.9
Weathered gneissic	0	0	0	0	0	0	0	0	0	0	0.4	0	0.5	0.6	0	0
Schistose	0	0	0	0	0	0.5	0	0	0.9	0	0	0	0	0	0	0.5
Weathered schistose	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Metasedimentary	2.4	2.4	2.4	6.2	4.6	3.5	2.3	2.4	0	5.9	8.1	2.5	3.7	10.4	6.2	3.2
Weathered metasedimentary	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0.6	0.9
Metagraywacke	0.5	1.5	0.5	3.1	2.0	4.0	2.7	0.8	0.4	2.3	2.6	3.1	3.2	2.2	0.6	2.3
Tillite	0	0	0	0	0	1.0	0	0.4	0	0	0	0	0	3.3	1.7	1.4
Quartzite	0.5	0	0	0	0	0	0	0	0	0.9	1.7	1.0	0	1.6	4.5	0

*Projected expansion value used, due to broken beam.

Table 5. Point-count percentage of each rock type in test beams with intermediate percent expansions in each triplicate set of beams (Phase I).

	Sample number															
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15
Percent Expansion	0.032	0.015	0.033	0.086	0.059	0.046	0.069	0.058	0.024	0.066	0.072	0.077	0.080	0.056	0.060	0.053
Sedimentary Rocks																
Dolomite	64.8	63.8	61.3	48.1	56.8	41.9	39.9	60.0	62.5	27.7	23.4	41.8	28.6	25.8	22.0	20.2
Laminated dolomite	0	1.0	3.0	2.1	2.9	1.4	0.8	2.5	0.8	2.2	0	0	3.6	0.6	2.0	0.5
Silty dolomite	1.4	1.0	2.2	0.5	1.5	0.5	2.0	2.9	0.8	4.8	1.9	1.6	3.2	0.6	2.5	0.5
Pyritic dolomite	0.9	0	0	0	0	0	0.4	0.4	4.2	0	0	0	0	0	0	0
Limestone	3.3	5.2	3.5	3.2	2.4	2.8	2.8	2.1	2.5	11.3	9.8	7.1	10.9	14.6	10.5	9.4
Cherty carbonate	4.7	4.3	0.9	3.2	2.4	4.7	2.4	5.4	4.6	1.7	1.9	5.4	4.6	2.8	5.5	6.7
Chert	9.9	5.2	11.3	25.1	19.9	26.0	24.6	5.0	7.5	20.3	21.0	16.3	18.2	18.0	20.0	26.0
Weathered carbonate	5.6	1.9	4.4	2.7	1.9	3.3	4.4	7.5	5.0	15.2	5.1	6.5	5.9	3.9	1.5	3.6
Ironstone	0	0	0	0	0.5	0	0	0	0	0.9	0	0.5	0	0.6	0	0
Shale	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0.5	0
Sandstone-siltstone	0.9	2.9	1.7	5.4	1.5	3.7	4.0	1.3	1.7	5.6	4.7	6.0	4.1	2.8	6.0	6.7
Igneous Rocks																
Mafic	0	3.3	3.5	1.1	0.5	3.7	1.6	4.2	2.9	1.3	1.4	1.1	2.3	3.4	9.0	2.7
Weathered mafic	0.5	0.5	0	1.1	0	0.5	0.8	0.4	0.4	0	0	0	0.9	0.6	2.0	2.2
Coarse felsic	0.5	1.0	0	0	0	0	1.6	0	0	0	8.9	0	0	1.1	1.0	0
Weathered coarse felsic	0	0	0.4	0	0.5	0	0	0	0	0	0	0	0	0	0	0
Fine felsic	0.9	0	0.4	0.5	0	0.5	0	0	0	0	2.8	2.7	0.9	0	0	0
Massive quartz	0	0	1.3	1.1	1.0	0	3.6	1.3	0	2.6	5.1	0.5	1.8	1.7	2.5	1.8
Metamorphic Rocks																
Gneissic	3.3	5.2	0.9	2.1	5.3	3.7	3.2	1.3	5.4	1.3	3.7	4.9	3.6	3.4	5.5	3.1
Weathered gneissic	0	0.5	0	0	0	0	0	0	0	0	0.5	0.5	0	0.6	0	1.4
Schistose	1.4	0	0	0	0	0	0	0	0	0.4	0	0	0	0.6	0	0.9
Weathered schistose	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Metasedimentary	1.9	2.9	2.2	2.7	1.5	3.3	5.6	3.3	0	2.6	6.5	4.4	8.2	10.7	6.5	9.9
Weathered metasedimentary	0	0	0	0	0	0	0	0.4	0	0	0.5	0	0.5	0	0	0
Metagraywacke	0	1.0	3.0	0	1.9	2.8	1.6	0.4	1.3	1.3	1.4	0.5	1.8	2.3	1.0	0.9
Tillite	0	0.5	0	0	0	0	0	0.4	0	0	0	0	0	3.9	1.5	1.4
Quartzite	0	0	0	1.1	0	0.5	0.4	1.3	0.4	0.4	1.4	0	0.9	2.3	0.5	2.2

Table 6. Point-count percentage of each rock type in test beams with lowest percent expansions in each triplicate set of beams (Phase I).

	Sample number															
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15
Percent Expansion	0.018	0.014	0.024	0.069	0.054	0.030	0.038	0.054	0.019	0.063	0.035	0.037	0.059	0.053	0.055	0.048
Sedimentary Rocks																
Oolomite	70.4	58.1	68.2	48.8	53.5	49.5	56.9	56.1	60.8	30.2	30.3	44.3	31.6	19.3	20.6	16.4
Laminated dolomite	0	4.2	3.9	1.9	1.5	2.4	1.6	4.0	0.4	5.6	1.8	1.5	1.5	0	3.0	0.4
Silty dolomite	0.4	0.5	0.4	1.0	2.0	0	0.8	1.6	3.4	6.5	1.8	2.0	2.4	0	1.5	0.4
Pyritic dolomite	1.3	0.9	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0
Limestone	2.2	5.1	2.6	5.2	0.5	2.4	2.0	3.6	3.8	10.2	7.8	6.5	5.9	9.9	11.6	6.6
Cherty carbonate	4.4	7.4	1.3	3.3	4.6	2.9	3.3	4.4	6.8	5.6	2.8	4.5	6.3	2.1	2.0	5.8
Chert	5.7	8.8	5.6	18.0	20.2	25.0	18.7	12.6	11.4	8.8	27.5	14.9	22.8	21.4	17.1	21.2
Weathered carbonate	5.7	6.5	2.6	3.3	4.0	3.9	1.6	7.9	3.8	17.2	1.4	4.0	5.8	8.3	4.0	6.6
Ironstone	0	0.5	0.4	0	0.5	0	0	0	0	0.5	0	1.0	0.5	0.5	0.5	0
Shale	0	0	0	0	0	0	0	0	0	0	0	1.0	0.5	0.5	2.5	0
Sandstone-siltstone	1.3	1.8	1.7	2.4	2.5	2.9	1.6	2.0	0.8	3.3	0	4.0	2.4	5.2	4.0	10.2
Igneous Rocks																
Mafic	2.6	1.4	2.2	1.4	2.0	1.9	1.2	0	2.5	0.5	1.8	3.5	0.5	2.6	8.5	3.5
Weathered mafic	0	0	0	0	0.5	0.5	0	0	0.4	0	0.5	0.5	0.5	0.5	1.0	0.9
Coarse felsic	0	0	0	0.5	0	0	3.7	0	0.8	0	1.8	0	0.5	0	0	0.4
Weathered coarse felsic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4
Fine felsic	0	0	1.3	0.5	0	0.5	1.2	0	0	0	1.8	1.0	1.5	0	0	1.3
Massive quartz	0	0	0.4	0.5	0.5	0.5	1.2	0.4	0.4	3.7	2.8	2.0	1.0	4.2	2.5	3.5
Metamorphic Rocks																
Gneissic	3.0	0.9	5.6	4.7	2.5	1.9	0.8	2.4	3.8	1.4	3.2	2.5	4.4	3.7	5.5	6.6
Weathered gneissic	1.3	0	0.9	0	0	0	0	0	0	0.5	1.4	0	0	0.5	0	0
Schistose	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0.5	0.4
Weathered schistose	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Metasedimentary	0.4	1.4	2.2	4.7	1.5	2.9	2.9	3.2	0.8	2.8	9.2	2.5	4.9	14.6	7.0	8.0
Weathered metasedimentary	0.4	0	0	0	0	0	0	0	0	0	0.5	0.5	0	1.0	0	0
Metagraywacke	0.9	2.8	0.9	2.8	3.0	2.9	1.6	1.6	0	0.9	1.8	3.0	3.4	2.1	1.0	4.0
Tillite	0	0	0	0	0.5	0	0.4	0	0	0	0	1.0	0.5	2.6	2.5	0
Quartzite	0	0	0	1.0	0	0	0.4	0.4	0	1.9	1.4	0	3.4	1.0	4.5	2.2

The cracked pebble data are summarized in table 7. Dolomite percentages of the samples range from 19 to 66 percent (table 3). Only 14 to 33 percent of the dolomite pebbles contain cracks, mostly single cracks that do not extend completely across the pebble (fig. 19). In contrast, chert percentages of the gravel samples range from 6 to 25 percent (table 3), and 38 to 66 percent of the chert pebbles (table 7) contain cracks. Chert pebbles commonly are cracked completely across the particle and often appear shattered by numerous cracks (fig. 19).

The striking difference between the tendency of chert and dolomite particles to crack is illustrated by the cluster patterns that result when the point-count percentage of chert and dolomite from all samples is plotted against the percentage of cracked pebbles in chert and dolomite (fig. 20). As a control on how much of the observed cracking occurred during freeze-thaw testing, two samples (numbers 2 and 10) were cast into beams, prepared, and point-counted without being freeze-thaw tested. This control data (fig. 20) gives an indication of how much the cracked pebble values are related to factors other than the freeze-thaw test. For sample 2, the amount of cracked chert rose from 11 to 55 percent, after freeze-thawing, whereas the amount of cracked dolomite increased only from 14 to 21 percent after freeze-thaw testing. In sample 10, cracked chert content rose from 6 to 46 percent after freeze-thaw testing, but cracked dolomite content increased only from 3 to 12 percent after freeze-thaw testing. Thus 40 to 44 percent of the chert content of samples 2 and 10 was cracked during freeze-thaw testing, while only 7 to 9 percent of the dolomite content was cracked during freeze-thaw testing. The similarity of the results from the two control samples leads us to conclude that the other samples probably reacted about the same to freeze-thaw testing.

A factor that may also affect the difference in cracked pebble values noted between samples 2 and 10 is that sample 2 was from a coarse gravel deposit that required crushing, while sample 10 was from a fine gravel deposit that did not. Thus, initially 5 percent more chert was cracked in sample 2 than in sample 10, and 9 percent more dolomite was cracked in sample 2 than in sample 10 (fig. 20).

A study of loose pebbles of chert and dolomite (3/4- to 1/2-inch size) split from samples 2 and 10 revealed the same trend in terms of freshly chipped or broken pebble surfaces: (1) 45 percent of the dolomite pebbles were broken in the crushed sample 2, and 11 percent were broken in the uncrushed sample 10; and (2) 25 percent of the chert pebbles were broken in the crushed sample 2, and 17 percent were broken in the uncrushed sample 10. Other material-handling operations probably caused most of the pebble breakage in the uncrushed sample 10. Thus, the cracked pebble (internal) and broken pebble (external) data vary directly, implying that crushing causes cracks within pebbles as well as breaking them. These comparisons also imply that the cracking and breaking of pebbles caused by crushing, while measurable, does not contribute to increased cracking or expansion during freeze-thaw testing. Furthermore, the amount of cracking due to crushing is insignificant compared to the amount of cracking caused by the freeze-thaw test in pebbles such as chert that seem to be susceptible to freeze-thaw expansion.

Comparison between percentages of minor rock types such as ironstone (table 3), and their respective percentages of cracked pebbles (table 7) generally is of limited value because there are too few ironstone pebbles in

Table 7. Point-count percentage of cracked pebbles of the total number of pebbles found of each rock type (table 6) in each triplicate set of test beams (Phase I).*

	Sample number															
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15
Sedimentary Rocks																
Dolomite	22.5	21.4	29.0	19.3	25.2	33.1	15.2	21.8	15.7	23.0	12.4	22.1	13.9	16.2	21.9	15.9
Laminated dolomite	0.0	41.2	31.8	13.3	18.8	6.3	0.0	34.8	20.0	30.0	0.0	60.0	16.7	16.7	50.0	0.0
Silty dolomite	0.0	33.3	12.5	11.1	0.0	0.0	0.0	35.7	7.1	5.7	15.0	30.8	7.1	20.0	21.4	0.0
Pyritic dolomite	9.1	0.0	-	-	-	-	0.0	100.0	36.4	0.0	-	-	-	-	-	-
Limestone	28.6	28.6	11.5	24.1	45.5	38.1	10.0	20.7	4.6	18.4	25.0	18.6	34.0	24.1	23.5	18.0
Cherty carbonate	6.7	12.9	18.2	35.3	26.3	45.5	28.6	14.6	22.2	20.0	0.0	38.5	37.0	41.2	31.8	23.8
Chert	59.6	55.0	50.0	55.4	50.8	56.8	50.9	71.1	56.5	59.2	45.4	65.6	54.2	52.4	58.7	38.3
Weathered carbonate	9.1	16.7	24.0	23.8	31.6	24.0	8.3	27.3	18.2	13.8	15.8	28.6	25.7	20.0	18.8	5.6
Ironstone	50.0	0.0	100.0	-	0.0	-	-	-	100.0	75.0	-	66.7	20.0	0.0	0.0	-
Shale	-	-	-	-	-	-	-	-	-	100.0	-	33.3	0.0	0.0	37.5	-
Sandstone-siltstone	14.3	0.0	18.2	22.7	33.3	19.0	5.3	0.0	0.0	9.7	0.0	6.3	13.0	0.0	3.7	6.7
Igneous Rocks																
Mafic	14.3	11.8	5.6	14.3	0.0	5.0	0.0	0.0	0.0	33.3	0.0	0.0	0.0	0.0	6.9	0.0
Weathered mafic	50.0	0.0	-	50.0	0.0	0.0	0.0	50.0	0.0	-	0.0	50.0	0.0	0.0	12.5	0.0
Coarse felsic	0.0	100.0	-	0.0	-	-	11.8	-	0.0	-	13.3	0.0	100.0	20.0	0.0	0.0
Weathered coarse felsic	-	-	100.0	-	0.0	-	-	-	-	-	-	-	-	-	-	0.0
Fine felsic	0.0	0.0	40.0	0.0	-	66.7	0.0	-	0.0	0.0	6.7	12.5	0.0	-	-	0.0
Massive quartz	-	33.3	25.0	16.7	0.0	0.0	6.7	28.6	0.0	23.5	30.8	57.1	75.0	35.7	40.0	16.7
Metamorphic Rocks																
Gneissic	20.0	5.3	25.0	5.3	4.4	17.4	0.0	5.3	31.0	0.0	20.8	0.0	16.0	5.3	18.5	5.7
Weathered gneissic	100.0	0.0	0.0	-	-	-	-	-	-	0.0	60.0	100.0	100.0	0.0	-	0.0
Schistose	33.3	-	-	-	-	0.0	-	-	0.0	0.0	0.0	-	-	0.0	0.0	0.0
Weathered schistose	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Metasedimentary	10.0	14.3	20.0	14.8	6.7	5.0	3.9	9.1	0.0	8.0	3.8	5.6	8.6	9.1	2.6	4.3
Weathered metasedimentary	0.0	-	-	-	-	-	-	100.0	-	-	0.0	0.0	0.0	0.0	100.0	0.0
Metagraywacke	0.0	0.0	0.0	0.0	7.1	20.0	0.0	0.0	0.0	10.0	0.0	0.0	11.8	0.0	0.0	0.0
Tillite	-	0.0	-	-	0.0	0.0	0.0	0.0	-	-	-	0.0	0.0	11.1	0.0	0.0
Quartzite	0.0	-	-	25.0	-	0.0	0.0	0.0	0.0	57.1	10.0	50.0	11.1	22.2	33.3	10.0

*A "-" indicates that rock type was not found in that three beam set; a "0" indicates that less than 0.05 percent of pebbles of that type were cracked.

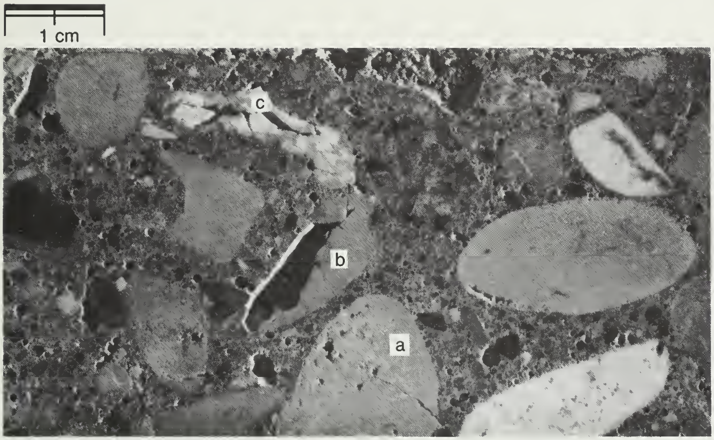


Figure 19. Polished slab surface showing; a partially cracked dolomite (a), and two shattered cherts (b and c).

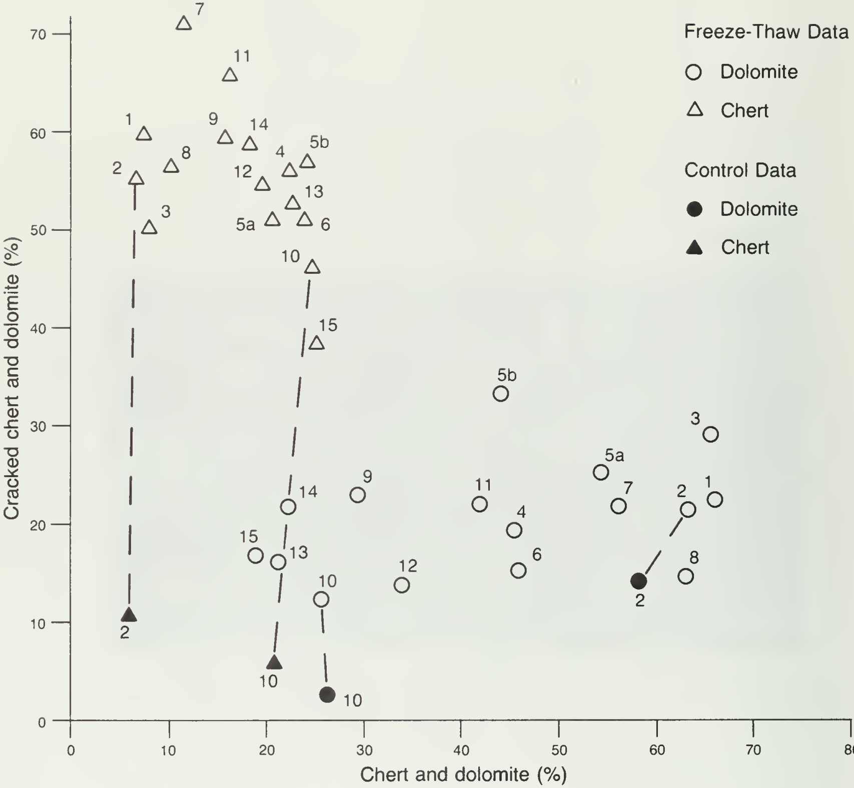


Figure 20. Comparison of percentage of chert and dolomite pebbles with the percentage of each that are cracked in all 16 sets of Phase I test beams (point-count data). Each point is identified by its sample number. Dashed lines connect values for the percentage of cracked chert and dolomite pebbles in "control" samples not subjected to freeze-thaw testing with equivalent values for samples that were subjected to testing.

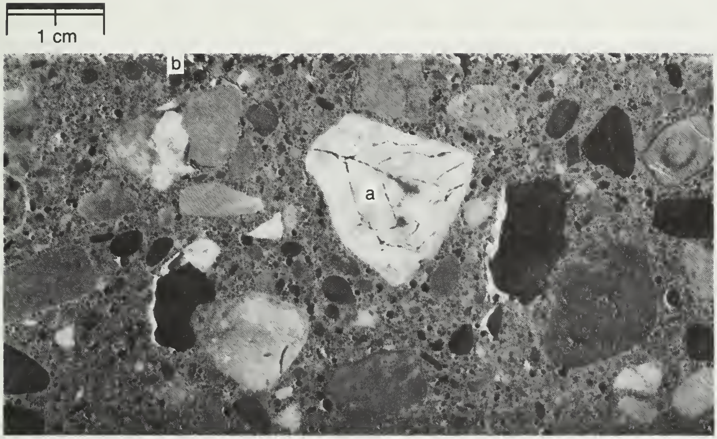


Figure 21. Polished slab surface showing a shattered chert pebble (a) with a crack in the cement matrix extending upward at about a 45° angle to the beam surface (b).

the sample to produce reliable data. Ironstone pebbles, which are known to be deleterious, range from zero to 100 percent cracked, but these percentages may be based on counts of only one to six pebbles (less than 1% of the total counts) in the three beams studied per sample. However, generalizations can be made about some moderately abundant rock types such as limestone, laminated dolomite, cherty carbonate, and weathered carbonate pebbles, in that they tend to be cracked more frequently than dolomite. Sandstone-siltstone and silty dolomite appear to be cracked less frequently than dolomite. Most igneous and metamorphic rock types especially mafics, gneisses, metasediments, and metagraywackes (with the exception of their weathered equivalents) tend to be less frequently cracked than dolomite.

In the test beams, surface cracks often connect popouts (fig. 14), suggesting that planes of weakness tend to develop between closely associated deleterious pebbles. Point-count studies of slab surfaces reveal that within the beams these cracks often extend to other cracked, deleterious pebbles (fig. 21). This evidence suggests that fracture and popout of expansive coarse-aggregate particles located near the surface of the beam may have little or no effect on the expansion of the test beam. However, when such expansive pebbles are located too far inside the beam to cause a popout, the same forces that fracture expansive pebbles cause cracks to propogate from them into the surrounding cement matrix. These cracks may extend through or around nearby innocuous particles, and contribute significantly to the expansion of the beam.

The only internal deterioration features in the test beams that could account for the expansion of the beams during freeze-thaw testing were the fractures in the pebbles and associated fractures in the matrix. Far too few reaction rims (indicating alkali-aggregate reactivity) were found during the study of slab surfaces to account for the test-beam expansion. It is believed that the use of type I, low-alkali Portland cement in the test beams and the relatively short test period (2 weeks curing and 7 weeks testing) minimized any potential chemical reactions between the cement and gravel.

Statistical analyses

The expansion values obtained by IDOT's freeze-thaw testing of Phase I samples and the rock-type percentages obtained by ISGS point-counting methods were evaluated, using procedures from the statistical programs known as the "Statistical Analysis System" (SAS) (SAS User's Guide: Basics, 1982 Edition, and Statistics, 1982 Edition). The SAS General Linear Models (GLM) procedures were used to generate a plot of each rock type versus test-beam expansion and to calculate various simple regressions. Similarly, the SAS Stepwise Regression procedures were used to calculate various multiple regressions.

GLM simple regression analyses were calculated in two ways. In the first round of analyses, rock-type data and expansion values from each of the 48 test beams (including one estimated value for a broken beam) were used. In the second round of analyses, average rock-type and expansion values from each triplicate set of test beams were used, giving a total of 16 samples. Table 8 lists the 13 rock types with the highest R-Square "Coefficient of Determination" values (Wonnacott and Wonnacott, 1981) and F Value numbers from the first round of GLM anlyses in decreasing order. Results from the second round of analyses are given in parentheses in table 8.

Table 8. Summary of simple regression analyses obtained using SAS General Linear Models procedures to evaluate the relationship of the content of each rock type (point-count data) to freeze-thaw expansion values.*

Rock Types	Slope	F Value	R-Square	Prob > F
Dolomite	- (-)	18 (11)	0.28 (0.43)	0.0001 (0.0056)
Sandstone-siltstone	+ (+)	17 (7)	0.28 (0.32)	0.0001 (0.0222)
Chert	+ (+)	15 (9)	0.24 (0.38)	0.0004 (0.0106)
Limestone	+ (+)	9 (5)	0.17 (0.25)	0.0039 (0.0463)
Pyritic dolomite	- (-)	6 (9)	0.12 (0.40)	0.0163 (0.0087)
Massive quartz	+ (+)	5 (4)	0.10 (0.24)	0.0271 (0.0530)
Ironstone	+ (+)	5 (2)	0.10 (0.13)	0.0297 (0.1776)
Silty dolomite	+ (+)	5 (2)	0.09 (0.12)	0.0374 (0.1824)
Weathered metasediment	+ (+)	4 (5)	0.09 (0.27)	0.0441 (0.0370)
Metasediment	+ (+)	4 (5)	0.08 (0.25)	0.0531 (0.0500)
Quartzite	+ (+)	3 (4)	0.06 (0.23)	0.0994 (0.0587)
Metagraywacke	+ (+)	2 (2)	0.05 (0.15)	0.1229 (0.1377)
Shale	+ (+)	2 (2)	0.05 (0.14)	0.1392 (0.1484)

*Includes analysis of data from all 48 test beams (degrees of freedom for the F test of 1 and 46), and in parentheses, analysis of averaged data from a triplicate set of beams for each of the 16 samples (degrees of freedom for the F test of 1 and 14).

The R-Square value is a numerical measure of the strength of the relationship between the amount of a given rock type in a beam or set of beams and the expansion of that beam or set of beams; it is the proportion of the variability in the expansion that can be explained by a linear relationship with rock-type content. Thus, as the R-Square value increases (from zero to 1), the strength of the relationship increases. For instance, an R-Square value of 0.25 means that for any rock type, only 25 percent of the total variation in expansion can be accounted for by the fitted regression of that rock type. The F Value tests how well the model (in this case the rock type pecentages), adjusted for the mean, accounts for the variability of the expansion of the beams. It is a value determined by dividing the variation (regression) that is attributed to the rock-type content (independent variables in the model), by the residual variation (error) that is not accounted for by the rock-type contents. An F Value of 5 or higher is considered to be in the 95 percent range of significance. The significance probability is labeled Prob > F, if it is small, it indicates significance. The range of significance is interpreted as follows:

- Prob > F greater than 0.1 is not significant
- Prob > F between 0.05 and 0.1 mildly significant
- Prob > F between 0.01 and 0.05 clearly significant

° Prob > F between 0.001 and 0.01 highly significant
° Prob > F less than 0.001 is very highly significant

In the first round pf analysis, the first four rock types listed in table 8 had F Values well above 5 and may be interpreted as being significant, even though only about one-fourth to one-fifth of the variability in expansion can be explained by a linear relationship with the rock-type data. Perhaps the variability could be better explained by some nonlinear relationship, but this possibility was not pursued. Dolomite, sandstone-siltstone, and chert had Prob > F values of less than 0.001 (table 8), which is considered to be very highly significant, and limestone had a Prob > F value of less than 0.01 which is considered highly significant. The next five rock types listed in table 8 (pyritic dolomite, massive quartz, ironstone, silty dolomite, and weathered metasediment) have somewhat lower F Value and R-Square values, but their Prob > F values are between 0.01 and 0.05, which indicates that even though their relationships with expansion are small, they may still be considered clearly significant. The last four rock types listed on table 8 (metasediment, quartzite, metagraywacke and shale) have statistical relationships to expansion that are not much lower than those of the five preceeding rock types and should be considered suspect, but at this stage they are tentatively interpreted not to be major causes of expansion.

The slope column in table 8 gives only the mathematical sign of the slope values from the equations for the linear regression lines calculated for each rock type. Figures 22 to 25 are plots of percent expansion versus point-count percentages of dolomite, chert, limestone, and sandstone-siltstone in the 48 test beams (first-round analyses). Although the F Value, R-Square, and Prob > F values for dolomite suggest that it has a highly significant relationship with expansion (table 8), its slope is negative and the magnitude of the regression line is very small (fig. 22). We conclude that dolomite is essentially nonexpansive and the observed negative slope is probably the result of dilution of the nonexpansive dolomite by other abundant and possibly more expansive rock types such as chert, sandstone-siltstone and limestone. These three rock types, along with dolomite, form the bulk of all the samples and, when the percentage of dolomite in a sample is lower, these rock types generally are more abundant and test beam expansion is greater. As shown in figures 23 to 25, values of the positive slopes of the regression lines for chert, limestone, and sandstone-siltstone are an order of magnitude greater than it is for dolomite. Such magnitudes indicate a direct relationship between test beam expansion and the percentages of these rock types in the beams. However, the relatively low R-Square values and results of other statistical tests indicate that the magnitudes of these calculated slopes cannot be used to infer the relative importance of one rock type or another as a cause of beam expansion.

A comparison of the first-round analyses values with the second-round values in table 8 shows that averaging the rock type and expansion data smooths out some of the variability and results in somewhat higher R-Square values. Averaging the data increases the apparent relationship between a given rock type and expansion. The fact that the F Value and R-Square of chert become higher than that of sandstone-siltstone is considered to be especially important, and we tentatively interpret this result as indicating that chert ranks first in causing increased expansion.

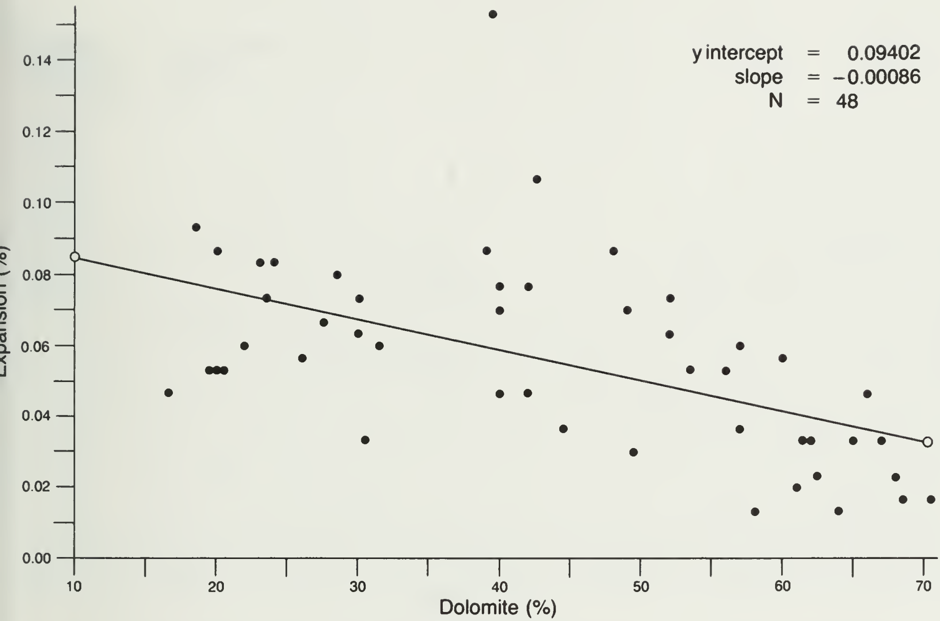


Figure 22. Percentage of dolomite (point-count data) compared to the percent expansion of each Phase I freeze-thaw test beam.

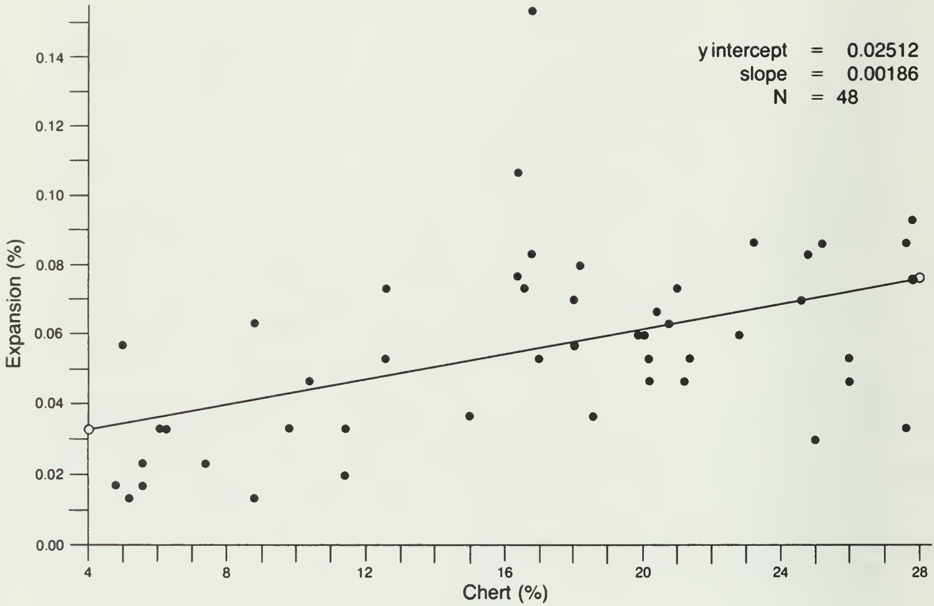
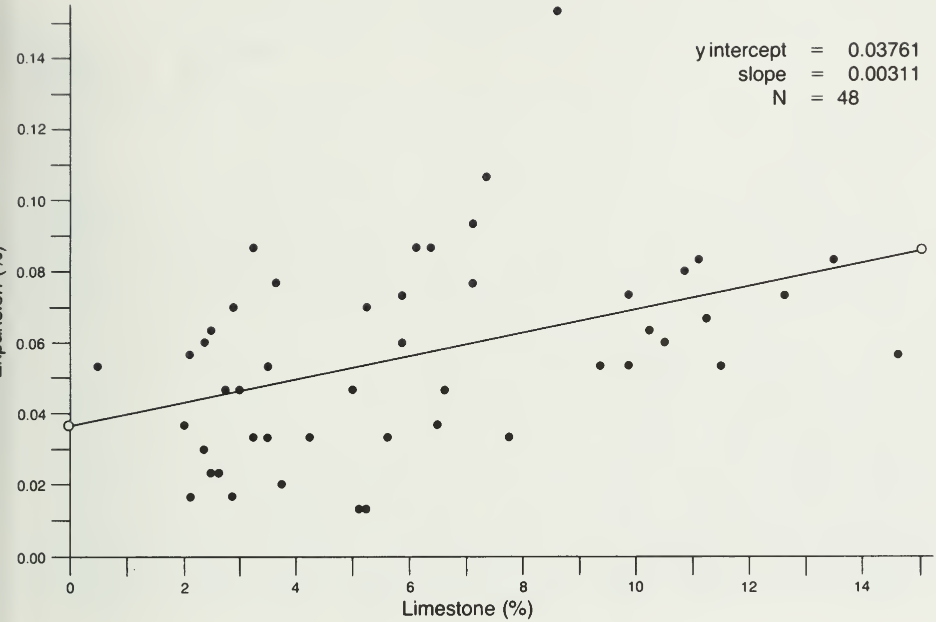


Figure 23. Percentage of chert (point-count data) compared to the percent expansion of each Phase I freeze-thaw test beam.



igure 24. Percentage of limestone (point-count data) compared to the percent expansion of each Phase I freeze-thaw test beam.

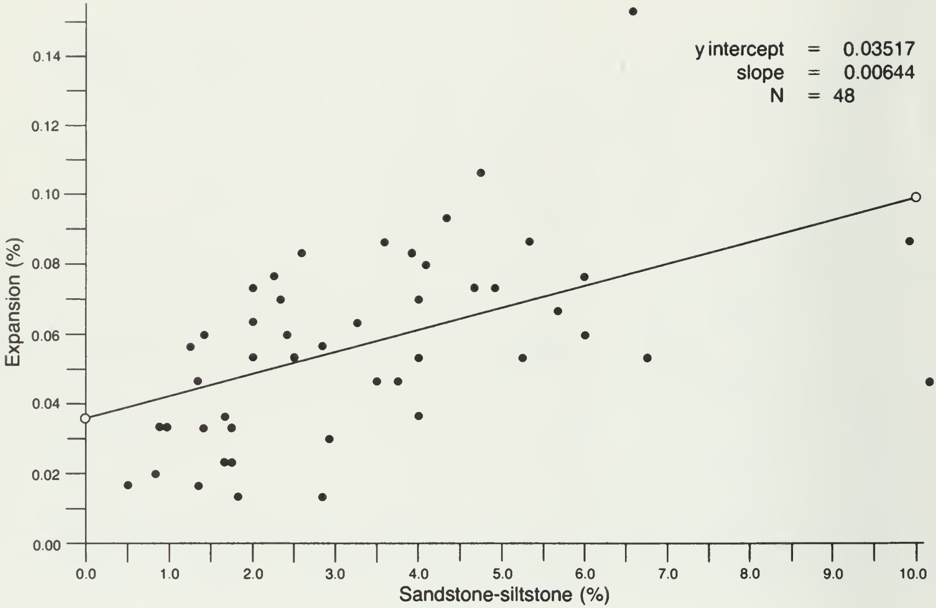


Figure 25. Percentage of sandstone-siltstone (point-count data) compared to the percent expansion of each Phase I freeze-thaw test beam.

Although R-Square values for sandstone-siltstone, chert, and limestone were increased in the round-two regression analysis, the F Value decreased and Prob > F values increased. Values of Prob > F range between 0.01 and 0.05 (clearly significant) for chert, sandstone-siltstone, and limestone. These reduced levels of significance (increased probability of error) result primarily from the lower degrees of freedom for the F test when the number of samples is decreased.

Ironstone, silty dolomite, and massive quartz, considered to have a clearly significant relationship to expansion in the first round of analysis (table 8), may not have a signifcant relationship, because in the second round of analysis, their Prob > F values are greater than 0.05. We are unable to explain why the R-Square and Prob > F statistical values for weathered metasediment and metasediment indicate a more significant relationship to expansion in the second-round analysis and do not consider them important. All of these statements are considered tentative because of the low R-Square values. All 11 rock types with positive slopes in table 8 were reevaluated, using a stepwise multiple regression procedure. The results of this statistical analysis are discussed in later paragraphs of this section.

Using the average freeze-thaw expansion percentages of each three test-beam set (second round) reduced the variability in the data and produced higher R-Square numbers. This suggests that the averaged data may be more representative of the original gravel samples than are data from the individual test beams. However, because the R-Square values for the second round of analyses remained comparatively low, more than three replicate test-beams may be needed per sample in order to obtain information that adequately represents the original gravel sample. The reduction in significance caused by the reduction of the number of measurements from 48 to 16 between the first and second round of analyses can also be interpreted to mean that additional rock-type and expansion data are needed from a greater number of test beams for each sample in order to increase the significance.

Multiple regression analyses also were applied to the point-count data. The SAS Stepwise Regression procedure was found to be the most suitable method for evaluating the interaction of various rock types with expansion. Rock types included in this procedure were those listed in table 8 that have positive slopes. Results of the stepwise regression procedure are given in table 9. As with the simple regression analyses, the multiple regression analyses were also calculated in two ways.

In the first round of analysis, rock-type data and expansion values from each of the 48 test beams were used, resulting in Model A (table 9). Only chert, ironstone, silty dolomite, and sandstone-siltstone from the 11 rock-types with positive slopes on table 8 met the 0.15 significance level for entry into the model. Chert probably contributed most to expansion, as is implied by its high F Value and low Prob > F. This four-member model has an R-Square of 0.55, indicating that 55 percent of the total variation in expansion may be accounted for by the fitted regression of Model A, and a Prob > F of 0.0001, indicating that the relationship of this model to expansion is significant at the 99 percent confidence level.

In the second round of analysis, rock-type data and expansion values for each set of triplicate test-beams were averaged, giving 16 sets of rock-type

Table 9. Summary of multiple regression analyses obtained using SAS Stepwise Regression procedure to identify rock types (point-count data) most closely related to freeze-thaw expansion.*

	Rock Types	F Value	Prob > F
Model A	Chert	13	0.0008
	Ironstone	9	0.0041
	Silty dolomite	8	0.0057
	Sandstone-siltstone	5	0.0273
Model B	Chert	20	0.0008
	Ironstone	14	0.0031
	Metagraywacke	4	0.0854

* Model A is derived from analysis of data from all 48 test beams (degrees of freedom for the F test of 4 and 43). Model B is derived from analysis of averaged data from the triplicate sets of beams for each of the 16 samples (degrees of freedom for the F test of 3 and 12).

data and 16 corresponding sets of expansion values, resulting in Model B (table 9). In this case only chert, ironstone and metagraywacke met the 0.15 significance level for entry into the model. As in Model A, chert apparently contributed most to expansion. Model B, with only three members, had a considerably higher R-Square of 0.72, indicating that 72 percent of the total variation in expansion is accounted for by the fitted regression of Model B. Its lower Prob > F of 0.0013 is still in the highly significant range.

As with the simple regression analyses, the multiple regression analyses produces a stronger relationship with expansion (R-Square of the model) when the 16 averaged sets of data were analyzed rather than the data from the individual beams. The multiple regression analyses strengthen the tentative conclusion that chert is the most likely cause of freeze-thaw expansion. Ironstone also is significantly related to expansion in both Models A and B. Despite the substitution of metagraywacke in Model B for silty dolomite and sandstone-siltstone in Model A, all three rock types probably should be considered suspect. However, although metagraywacke is an integral part of Model B, its F Value is so low and its Prob > F is so high that it is no more than mildly significant, and, compared to chert and ironstone, its contribution to the average expansion of the beams is probably minor. Also, the higher R-Square of Model B for the multiple regression analysis again suggests that data from individual test beams are less representative of the gravel sample than are the three-beam averages, and that data averaged from more than three replicates of each sample would probably be even more representative.

In summary, the results of the simple and multiple regression analyses indicate that almost certainly chert, and probably ironstone contribute to freeze-thaw expansion. Silty dolomite and sandstone-siltstone may also contribute to expansion. Metagraywacke probably should be considered only

suspect. The multiple regression analysis also indicates that limestone, massive quartz, weathered metasediment, metasediment, quartzite, and shale are probably not suspect.

These conclusions must always be qualified by the fact that they apply only to the relative concentrations of each rock type present in the tested samples. Other samples, with different physical characteristics or greater amounts of rock types that are rare in the tested samples, could very possibly exhibit significant expansion during freeze-thaw testing.

Variability of test results

The statistical analyses of our data and our conclusions on the relationships between rock types and expansion highlight the problem of the variability in expansion among test beams of the same sample, and suggest that the average values for both expansion and rock type composition from the replicate beams are more representative than values from individual beams. Chert is probably the rock type most highly related to freeze-thaw expansion, but in the three-beam sets, the beam with the highest expansion does not always contain the highest amount of chert (see tables 4, 5, and 6).

Further evidence of the inherent variability of the expansion of test beams containing gravel aggregate is shown in table 10, in which previous expansion data on samples from sources used in this study are compared with those obtained during this study. For example, for samples 1 and 2 only two sets of three test beams were available, and the lowest expansion value of the present study's test beams are higher than the highest expansion for the previous test beams. In contrast, for sample 4, the highest expansion value of the present study's test beams is lower than the lowest expansion value of the previous three sets of test beams. However the average expansion values for most of the present study samples are relatively close to the averages of previous samples, despite the extreme range of low and high expansion values of some samples where multiple sets of test beams are available. The most noticeable differences concern sample 7, in which the 0.019 percent average expansion of three previous samples is much lower than the 0.050 percent average of six test beams run on the present sample. As the test is currently conducted, the variability of expansion data is so great that data from more than one set of freeze-thaw test beams is needed to evaluate the quality of aggregates in stockpiles. The number of sets required is not known, but probably could be estimated with some statistical studies of the data included in this report.

Thus, one or more factors other than the percentage of deleterious pebble types in a gravel sample can strongly affect test beam expansion. The simplest and most likely explanation (other than improperly made beams, or measurement errors during the test) is that deleterious pebbles may occupy different positions within different test beams, and that some positions are more critical to beam expansion than others. That is, deleterious pebbles located in the central core of the beam, centering around the axial line between the measuring pins (fig. 4, sketch), and especially just under the measuring pins, probably have more effect on beam expansion than deleterious pebbles located near the surface of the beam.

Table 10. Comparison of IDOT freeze-thaw expansion values obtained before this study started with those obtained during this study.*

Sample No.	Previous Sets of Freeze-Thaw Test Beams: Total Beams	Broken Beams	Percent Expansion: Average	Low - High	Present Study Freeze-Thaw Test Beams: Total Beams	Broken Beams	Percent Expansion: Average	Low - High
1	3	0	0.006	0.000-0.012	3	1	0.025	0.018-0.032
2	3	0	0.008	0.004-0.010	3	0	0.016	0.014-0.018
3	12	0	0.023	0.006-0.085	3	0	0.030	0.024-0.034
4	9	0	0.130	0.101-0.180	3	0	0.081	0.069-0.086
5	18	0	0.070	0.030-0.147				
5a					6	0	0.058	0.042-0.073
5b					6	0	0.034	0.025-0.046
6	9	0	0.061	0.046-0.089	3	0	0.062	0.038-0.079
7	9	0	0.019	0.006-0.034	6	0	0.050	0.029-0.076
8	12	0	0.043	0.009-0.095	3	0	0.030	0.019-0.046
9	11	1	0.053	0.021-0.089	3	0	0.067	0.063-0.072
10	20	1	0.059	0.019-0.219	3	0	0.063	0.035-0.082
11	19	2	0.116	0.013-0.466	3	0	0.089	0.037-0.154
12	15	0	0.056	0.020-0.114	3	0	0.082	0.059-0.106
13	17	1	0.057	0.017-0.095	3	0	0.067	0.053-0.092
14	18	0	0.066	0.024-0.224	3	0	0.066	0.055-0.083
15	12	0	0.085	0.033-0.147	3	0	0.063	0.048-0.088

*Previous samples probably represent different stockpiles from those of the present study samples, but are from the same pits (sources).

These data and their interpretation must be used with caution, because only 220 gravel point counts were made per beam, and the variability in chert contents (for instance, 20% in the three sample 6 beams) could be in part accounted for as "probable percentage error" (Brewer, 1964). Additional study of the distribution of deleterious rock types in the beams may help resolve the source of this variability.

IDOT aggregate quality test data

IDOT's routine aggregate quality tests (table 11) were also performed in IDOT's Materials Testing Laboratory on splits of all gravel samples included in this study. These data were statistically analyzed against the average freeze-thaw expansion values of the Phase I test beams, using the SAS General Linear Models simple regresssion analysis (table 12). The tests are listed in table 12 in the order of their significance in explaining the expansion data and their variability. The linear regression analysis of the low specific gravity (<2.35) chert data shows a very strong relationship with freeze-thaw test-beam expansion (fig. 26). Its Prob > F value indicates that this data is very highly significant. The analyses of the total chert data, total sample

Table 11. Results of IDOT Materials Testing Laboratory aggregate quality tests on the 16 study samples.

Laboratory Tests	Sample number															
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15
Total Chert Content (wt. %)	4.1	4.7	7.5	19.1	14.9	15.1	16.4	9.9	6.6	16.5	19.6	11.7	15.0	14.7	9.2	17.4
Chert >2.35 S.G.$^+$ (wt. %)	3.7	4.5	6.9	16.8	13.7	14.1	15.0	8.9	6.0	14.6	17.6	10.1	12.7	12.6	8.2	14.5
Deleterious Gravel Content (wt. %)																
Chert <2.35 S.G.$^+$	0.4	0.2	0.6	2.3	1.2	1.0	1.4	1.0	0.6	1.9	2.0	1.6	2.3	2.1	1.0	2.9
Soft & Unsound	0.9	1.6	1.1	2.3	0.9	0.3	1.6	1.8	1.0	4.7	0.6	2.5	2.8	0.5	2.1	0.7
Others*										0.1						0.1
Total	1.3	1.8	1.7	4.6	2.1	1.3	3.0	2.8	1.6	6.7	2.6	4.1	5.1	2.6	3.1	3.7
Specific Gravity of Total Sample	2.73	2.72	2.69	2.65	2.68	2.69	2.68	2.69	2.68	2.59	2.63	2.66	2.64	2.62	2.67	2.64
Na_2SO_4 Soundness (wt. % loss)	4.8	4.5	5.7	7.0	5.5	4.1	4.7	5.3	6.7	8.6	8.1	6.7	6.9	1.4	4.2	4.0
L.A. Abrasion (wt. % loss)	25.5	25.3	24.2	27.2	22.4	21.7	26.0	25.4	27.0	28.3	25.3	26.0	25.0	22.2	22.1	20.2
Water Absorption (wt. % gain)	3.7	1.9	1.9	2.5	1.7	1.3	1.5	2.0	1.9	3.1	1.8	2.0	1.8	1.8	1.5	1.5

*Shale in sample 9; coal in sample 15.
$^+$S.G. = specific gravity

Table 12. Summary of simple regression analyses using SAS General Linear Models procedure comparing data from each IDOT aggregate quality test with average freeze-thaw expansion data (Phase I) of the study samples.†

Laboratory Tests*	No. of samples	Slope	F Value	Prob > F	R-Square
Chert <2.35 S.G.+	16	+	21.59	0.0004	0.61
Total Chert	16	+	12.91	0.0029	0.48
Total Sample S.G.	16	+	12.13	0.0037	0.46
Chert >2.35 S.G.	16	+	10.78	0.0054	0.43
Soft & Unsound	16	+	3.36	0.0881	0.19
Na_2SO_4 Soundness	16	+	0.81	0.3824	0.05
Absorption	16	+	0.20	0.6632	0.01
L.A. Abrasion	16	+	0.02	0.8862	0.00

*IDOT Materials Testing Laboratory aggregate quality tests.
+S.G. = specific gravity
†Degrees of freedom for the F test are 1 and 14.

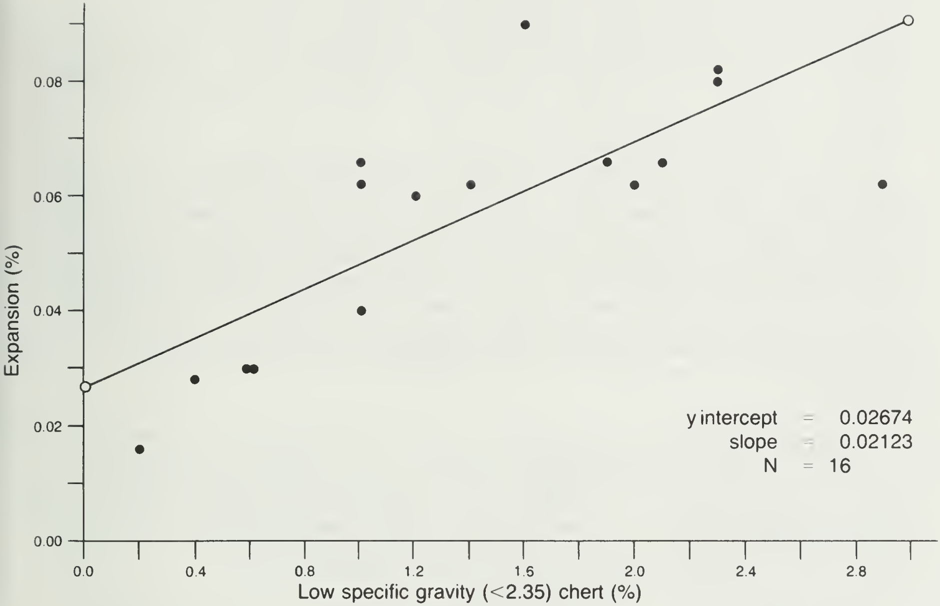


Figure 26. Weight percent of low specific gravity (<2.35) chert from table 11 compared to the average percent expansion of the 16 sets of triplicate test beams (Phase I).

specific gravity data, and high specific gravity (> 2.35) chert data (table 12) also show a fairly strong relationship between the test data and average expansion. The Prob > F values indicate that all three of these tests are highly significant. Analyses of the test data on soft and unsound material indicate no more than a mildly significant relationship with freeze-thaw test-beam expansion. Analyses of the Na_2SO_4 soundness, L.A. abrasion and absorption test data indicate that the data from these tests are unrelated to expansion in Illinois gravels. This comparison confirms IDOT's conclusion that some other test is needed to detect coarse aggregates susceptible to "D-cracking." However, data from the low specific gravity (< 2.35) chert test will help achieve this objective.

When the data from tables 8 and 9 are compared with table 12 data, it becomes clear that the content of chert in the test beams is related to the amount of expansion of the beams. Low specific gravity chert (table 12) is strongly related to test-beam expansion, but total chert, total sample specific gravity, and high specific gravity chert also are related to test-beam expansion to a significant degree. It seems clear that chert needs to be studied in more detail to substantiate these conclusions and to define the limiting specific gravity and other physical characteristics of chert that may be responsible for the expansion. This information would be useful in devising methods to economically remove deleterious chert from gravel aggregate.

The nearly identical significance of the total chert data and the specific gravity of the total sample data (table 12) with respect to expansion is interpreted to mean that the presence of relatively small amounts of low specific gravity chert in the study samples affects both of these sets of IDOT test data about equally. However, the extra work involved in obtaining low specific gravity chert data compared to obtaining data on the specific gravity of the total sample is considered to be very worthwhile.

The effect of minor rock types such as ironstone and silty dolomite on expansion is not detected very well in IDOT's routine aggregate quality tests. An assortment of these minor rock types is probably included in IDOT's lab test for soft and unsound material, but apparently not enough for this test to be very significant with respect to expansion.

PHASE II: FREEZE-THAW TESTING OF SELECTED GROUPS OF ROCK TYPES

Experimental design

In Phase II, freeze-thaw testing was conducted on individual rock types and groups of rock types. An additional split (60 pounds) of gravel in the designated weights of each size fraction was then taken from each bulk study sample. Each gravel particle in these splits was identified and sorted into the 28 rock type categories (see appendix). Approximately 200,000 rock type identifications were required to accomplish this task. These tests were made to test our preliminary conclusion that chert (especially low specific gravity chert), along with ironstone and probably silty dolomite, sandstone-siltstone, and possibly metagraywacke, are largely responsible for freeze-thaw expansion of the test beams.

After the samples were separated by size and rock types, the following procedure was used to cast the beams. The amount of each rock type obtained was augmented by a sufficient amount of a standard, non-expansive crushed dolomite to make a new set of test beams. For example, if a 60-pound sample split contained 10 pounds of chert, that 10-pound sub-sample of chert was mixed with 50 pounds of standard, nonexpansive crushed dolomite to obtain the 60 pounds of coarse aggregate, all in the proper size ranges, needed to make the test beams. Then the expansion resulting from freeze-thaw testing these beams could be attributed only to the chert.

For the first five samples studied in Phase II, every rock type except those present in trace amounts (<0.05%), was individually cast into a set of test beams. Freeze-thaw testing of these sets of test beams produced excellent expansion data on dolomite and chert; however, the other less abundant rock types usually did not create detectable expansion, probably because there were insufficient quantities of those rock types in the test beams. Therefore, the procedure was modified for the last 11 samples studied: they were all separated into the same 28 rock types, but for freeze-thaw testing the rock types were recombined into five groups of rock types (table 13).

Table 13. Classification of rock-type groups for Phase II series of freeze-thaw tests.

Group 1	Group 2	Group 3	Group 4	Group 5
Chert	Dolomite	Laminated dolomite	Coarse felsic	Ironstone
		Pyritic dolomite	Fine felsic	Silty dolomite
		Limestone	Mafic	Sandstone-siltstone
		Cherty carbonate	Quartzite	Shale
			Metasedimentary	Conglomerate
			Metagraywacke	Weathered coarse felsic
			Tillite	Weathered fine felsic
			Gneissic	Weathered mafic
			Schistose	Weathered metasedimentary
			Quartz	Weathered gneissic
				Weathered schistose
				Weathered carbonate

These groupings were chosen to: (a) provide independent testing for chert (group 1) and dolomite (group 2), the only rock types abundant enough to be individually tested in all samples; (b) provide a minimum of 6 pounds combined weight of rock types in the remaining groups (10% of the 60 pound sample); (c) provide a separate group of sedimentary rocks (group 3); (d) provide a separate group of unweathered igneous and metamorphic rocks (group 4); and (e) provide a group of suspected contributors to expansion that are present only in very small amounts including ironstone, silty dolomite, sandstone-siltstone (on the basis of Phase I data), and all weathered rock types and incompletely consolidated sediments considered unsound in other IDOT aggregate quality tests (group 5).

Another series of tests served as an additional check on the portion of the total expansion caused by chert versus other rock types. Splits of five selected study samples were obtained of sufficient size to allow two separate sets of samples to be created by separating the chert from the rest of the gravel. One sample set consisted of 60-pound samples of chert-free gravel, and the other set of pure chert, in the amounts found in the original pebble separation data for the respective samples. Thus, chert-free gravel and the separated chert from these sample splits could each be freeze-thaw tested separately.

In the following tables, the amounts of each rock type identified and sorted from each of the 16 study samples are presented as percentages of the sample weight retained on each sieve size. Rock-type data on an additional sample from a valley-train deposit in the Mississippi River valley that was not freeze-thaw tested are presented for comparison with the rock type content of the other gravel deposit areas. Cracks and popouts on test-beam surfaces were sketched and described as in the Phase I tests. Statistical analyses were made by comparing the weight percent of each of the five groups of rock types versus the freeze-thaw expansion percentages of the respective sets of test beams, and then comparing the weight percent of each rock type within each group versus the test-beam expansion values for its respective group.

Pebble identification data

The sorting of the 60-pound samples into rock types was done by using the identification methods described previously and in the appendix. The percentages by weight of the rock types for each 60-pound sample are presented in tables 14 through 19. Tables 14, 15, 16, and 17 show the percentages of each rock type found in the 3/4-inch, 1/2-inch, 3/8-inch, and number 4-mesh size ranges respectively. IDOT's concrete test-batch formula calls for 3 pounds of 1- to 3/4-inch material, 24 pounds of 3/4- to 1/2-inch material, 12 pounds of 1/2- to 3/8-inch material, and 21 pounds of 3/8-inch to number 4-mesh size material. This coarse aggregate gradation simulates the actual particle-size distribution of gravel as used in Portland cement highway pavement. These amounts were used for all samples except 5a and 5b, in which no 1- to 3/4-inch material was present; in order to bring these samples up to the required 60 pounds, the weights of each of the three finer sizes were increased by one pound.

Rock type variations

The major gravel deposits in Illinois from which the study samples were obtained differ in their rock type contents (table 18). These data are summarized in table 19, in which closely related rock types are lumped together; the samples are arranged according to the location of the outwash deposit where they originated, and identified by stratigraphic names (Willman and Frye, 1970) as either the Batavia Member (outwash-plain deposits) or the Mackinaw Member (valley-train deposits). Both of these types of deposits are members of the geologic unit known as the Henry Formation of Wisconsinan age. Table 19 indicates that, for the samples studied, dolomite is most abundant (63% to 67%) in McHenry County outwash plains and the closely related Fox River valley-train deposits, and chert is least abundant (5 to 10%) in these

Table 14. Weight percent of each rock type passing a 1-inch and retained on a 3/4-inch square aperture sieve.[+]

	Sample number																
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15	*
Sedimentary Rocks																	
Dolomite	61.5	64.9	58.8	53.9			47.8	60.4	62.0	44.3	21.9	27.2	27.0	19.6	17.0	18.0	1.7
Laminated dolomite	9.1	0	9.2	0.9			1.2	3.7	3.5	0	0.6	3.1	5.9	2.1	6.0	7.7	0
Silty dolomite	0	3.3	0	0.9			0	0.8	0	6.2	2.6	2.1	4.8	2.1	1.0	2.1	0.2
Pyritic dolomite	4.1	4.1	5.7	0			0	0	0	0	0	1.1	0	0	0	0	0
Limestone	1.9	2.2	1.6	1.7			1.5	3.9	7.6	1.2	10.4	8.8	17.2	6.8	5.5	7.4	2.7
Cherty carbonate	8.3	8.3	6.0	10.0			9.4	14.0	4.8	4.5	2.1	12.4	2.2	6.3	7.6	2.7	3.1
Chert	0	2.9	5.6	10.9			14.0	8.8	4.2	15.8	24.0	16.6	8.5	24.6	14.5	19.7	29.7
Weathered carbonate	2.8	0	3.2	2.1			11.7	1.4	3.0	7.6	6.2	3.8	4.7	1.5	0	0.8	0.3
Ironstone	0	0	0	0			0	0	0	0	0	0	0	0	0	0	1.9
Shale	0	0	0	0			0	0	0	0	0	0	0	0.7	0	0	0
Sandstone-siltstone	0.5	2.5	1.7	5.0			2.4	1.1	0	5.4	1.5	5.5	4.9	1.8	3.8	4.8	1.8
Conglomerate	0	0	0	0			0	0	0	0	1.5	0	0	2.0	0	0	0.4
Igneous Rocks																	
Mafic	5.9	6.4	2.9	0			0.6	0	6.8	6.0	1.0	5.4	4.0	4.4	10.2	5.2	2.3
Weathered mafic	0	0	0	0			0	0	0	0	1.2	0	0	0	1.2	2.4	0
Coarse felsic	0	0.7	0	0			0	0	1.0	0	0	0	0	0	0	0	2.4
Weathered coarse felsic	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0.2
Fine felsic	1.2	0	0	1.9			1.6	0	0	0	5.4	0.8	0	0	0	0.7	13.0
Weathered fine felsic	0	0	0	0			0	0	0	0	0	0	0	0	0	0	0
Massive quartz	0	0	0	0			0	0	0	0	2.0	0	0	1.6	0	0	1.4
Metamorphic Rocks																	
Gneissic	1.4	3.2	5.3	6.5			3.4	2.8	3.7	0.9	7.7	4.1	11.8	8.6	13.6	12.3	22.0
Weathered gneissic	0	0	0	0.9			0	0	0	0	1.4	0	0	1.9	0	1.5	0.9
Schistose	1.6	0	0	1.6			1.7	0	0	0	0	0	0	0	0	3.5	0
Weathered schistose	0	0	0	0			0	0	0	0	0	0	0	0	0	1.1	0
Metasedimentary	1.0	1.5	0	3.5			1.5	1.3	3.4	5.5	5.8	6.9	3.9	12.0	11.1	5.1	12.9
Weathered metasedimentary	0	0	0	0			0	0	0	0	0	0	0	0	1.5	0	0.2
Metagraywacke	0.7	0	0	0			0	1.7	0	2.5	2.1	2.3	2.5	0	0	2.3	1.4
Tillite	0	0	0	0			0	0	0	0	0	0	0	1.7	2.3	0	0
Quartzite	0	0	0	0			3.7	0	0	0	2.5	0	2.5	2.3	4.7	2.6	1.5

*See note on table 19.

[+]The letters "TR" designate the presence of trace amounts (<0.05%) of material. The number "0" designates no material was present. Samples 5a and 5b contained no gravel in this size range.

Table 15. Weight percent of each rock type passing a 3/4-inch and retained on a 1/2-inch square aperture sieve.+

	Sample number																
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15	*
Sedimentary Rocks																	
Dolomite	63.9	61.0	57.7	43.6	52.1	45.1	53.8	60.3	66.3	33.4	19.4	33.4	28.7	14.5	19.2	21.8	2.6
Laminated dolomite	4.1	5.3	2.9	4.0	2.3	1.6	1.4	1.5	3.5	1.8	2.4	2.1	2.4	2.0	3.1	1.3	TR
Silty dolomite	0.7	1.1	3.1	2.8	2.1	1.9	0.4	1.8	0.2	6.2	0.7	3.2	2.1	3.2	1.8	0.5	0.4
Pyritic dolomite	1.7	1.3	3.4	0.5	0.8	1.0	0	1.7	0.2	0.3	0	0.4	0.8	0.1	0.3	0	TR
Limestone	4.1	3.0	3.5	2.5	2.4	1.8	2.7	1.9	3.9	7.7	6.0	7.9	9.3	9.1	9.1	10.2	1.9
Cherty carbonate	5.6	4.7	8.0	7.8	5.0	5.7	5.1	10.3	4.7	7.1	3.2	9.9	8.1	12.2	9.9	7.3	3.3
Chert	3.5	4.0	6.5	18.4	17.5	18.2	14.7	9.4	6.0	13.9	24.7	14.5	16.0	16.9	14.2	20.2	23.7
Weathered carbonate	3.3	3.3	3.3	4.9	1.8	1.9	8.3	4.3	4.5	6.8	6.1	3.3	5.0	2.3	2.8	2.8	0.7
Ironstone	0.5	0.6	0.2	0.1	TR	0	0	0.1	0	1.5	0.3	1.1	0.6	0.3	0.3	0.2	1.5
Shale	0.1	0.3	0.3	0.1	TR	TR	TR	0	0	0.4	0	0.4	0.2	0.6	1.4	0	0.1
Sandstone-siltstone	2.5	1.7	2.2	2.6	2.2	2.3	2.5	1.2	2.4	5.6	6.5	4.0	3.6	5.0	4.8	6.4	1.4
Conglomerate	0	0.1	0	0	0	TR	0	0	0	0.3	0.2	0	0.2	0.2	0.3	0.1	0
Igneous Rocks																	
Mafic	3.9	5.6	2.4	2.6	1.8	5.0	2.2	1.8	1.5	3.7	2.0	4.6	4.2	5.6	6.0	4.6	4.1
Weathered mafic	0.1	0.5	0.1	0.1	0.1	0.1	0.3	0.1	0.3	0.3	0.6	0.2	0.3	0.4	0.2	0.2	0.3
Coarse felsic	0.2	0.3	0.2	0.3	0.3	0.8	0.1	0.2	0.3	0.1	0.4	0.4	0.4	0.4	0.3	0.1	1.3
Weathered coarse felsic	0	0	0	0	TR	0	0	0	0.1	0	0	0	0	0.1	0	0.1	TR
Fine felsic	0.4	0.4	0.3	0.3	0.3	1.1	0.3	0.5	0.2	0.2	6.9	1.3	2.6	0.1	0.1	0.3	9.8
Weathered fine felsic	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0.1	0	0	TR
Massive quartz	TR	0	0.2	0.3	0.3	0.2	0.4	TR	0.1	0.6	1.9	0.5	1.5	0.8	0.5	0.7	2.1
Metamorphic Rocks																	
Gneissic	2.7	3.8	2.5	4.7	4.5	5.0	2.9	1.7	3.3	3.6	9.1	5.6	5.7	9.4	9.2	7.0	20.4
Weathered gneissic	0.2	0.2	0.1	0.2	0.3	0.2	0.2	TR	0.4	0.4	1.2	0.3	0.2	0.5	0.4	0.3	1.1
Schistose	1.0	0.4	0.2	0.2	0.1	0.4	0.5	0.2	0.5	0.3	0.5	0.2	TR	0.6	0.2	0.8	0.2
Weathered schistose	TR	0.1	0	0	0	0	0.1	0	0	0	0	0	0	0.1	0	TR	TR
Metasedimentary	0.8	1.4	1.7	2.6	2.7	5.0	2.5	1.6	0.7	3.7	5.0	5.2	6.5	9.1	9.3	9.1	17.3
Weathered metasedimentary	0	0	0	0.1	0	0	0	0	0	0	0	0	0.1	0.1	TR	0	0.6
Metagraywacke	0.7	0.9	1.3	0.7	1.6	2.3	0.8	1.3	0.7	1.3	1.7	1.2	0.8	0.9	1.0	1.2	3.4
Tillite	0	0	0	0	0.2	0.1	0.1	0	0	0.3	0.1	0.2	0	2.1	2.6	2.5	0.1
Quartzite	0	0.2	0.1	0.6	1.1	1.3	1.0	0.1	0.3	0.2	1.2	0.7	0.7	3.3	3.1	2.3	3.6

*See note on table 19.
+The letters "TR" designate the presence of trace amounts (<0.05%) of material. The number "0" designates no material was present.

Table 16. Weight percent of each rock type passing a 1/2-inch and retained on a 3/8-inch square aperature sieve.+

	Sample number																
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15	*
Sedimentary Rocks																	
Dolomite	62.0	62.7	55.7	39.8	54.4	46.0	47.6	54.7	58.3	31.0	22.5	36.3	29.0	15.3	20.8	21.7	1.4
Laminated dolomite	2.2	1.9	1.8	3.1	1.9	1.1	1.9	2.5	4.3	1.8	2.3	1.1	0.5	2.7	2.2	0.5	0
Silty dolomite	1.8	2.0	3.2	3.0	1.6	1.2	0.6	1.7	0.7	4.3	1.1	2.4	2.5	2.2	2.6	0.5	0
Pyritic dolomite	0.7	0.5	2.7	0.4	0.7	1.6	0	1.8	0.2	0.4	0	0.1	0.3	0.1	0.1	0	0
Limestone	5.7	4.7	4.9	4.2	3.3	2.2	3.5	2.5	4.3	7.6	5.6	8.6	9.3	10.2	11.7	9.5	2.5
Cherty carbonate	3.5	4.5	8.2	7.5	4.5	4.0	5.4	10.5	7.9	7.2	5.6	7.8	7.9	9.2	8.4	5.8	2.5
Chert	5.1	5.9	8.2	21.1	16.5	20.4	20.1	10.6	6.9	15.5	18.2	14.0	16.2	19.2	15.7	24.4	25.4
Weathered carbonate	6.7	2.2	3.1	3.9	3.5	1.9	6.1	5.1	6.0	10.1	6.4	6.5	7.0	1.9	2.2	1.2	0.6
Ironstone	0.5	0.7	0.3	0.2	0	0.0	0	0.1	0.1	1.4	TR	1.0	0.7	0.5	0.6	0.2	1.4
Shale	TR	0.4	0.1	TR	0.1	TR	TR	0	0	1.0	0	0.5	0.5	0.6	1.4	0.1	0.1
Sandstone-siltstone	3.3	2.1	3.2	2.4	2.0	2.2	4.3	1.8	2.7	5.5	7.7	4.6	4.5	5.6	5.2	8.0	1.3
Conglomerate	0	0.1	0.1	0	0	0	0	0	0	0.5	0.2	0	0.4	0.3	0.4	0.1	0
Igneous Rocks																	
Mafic	3.0	4.8	2.3	2.7	1.5	4.6	1.2	2.2	1.2	2.2	2.6	3.9	3.4	6.5	5.8	4.7	4.1
Weathered mafic	0.5	0.8	0.3	0.2	0.1	0	0.5	0	0.9	0.7	0.6	0.1	0.1	0.3	TR	0.4	0.6
Coarse felsic	0.3	0.6	0.4	0.3	0.3	0.3	0.2	0.1	0.2	0.2	0.6	0.4	0.5	0.4	0.2	0.1	1.5
Weathered coarse felsic	0	0.1	0	TR	0	0	0	0	TR	0	0.2	0	0	0	0	0	0.2
Fine felsic	0.2	0.3	0.3	0.6	0.6	0.8	0.6	0.4	0.3	0.3	3.9	0.9	2.0	0.1	0.1	0.2	10.3
Weathered fine felsic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
Massive quartz	TR	0.2	0.1	0.7	0.6	0.5	0.8	0.2	0.2	1.7	4.2	0.6	2.0	1.0	0.3	1.6	2.6
Metamorphic Rocks																	
Gneissic	1.1	2.6	2.4	4.0	3.0	5.3	2.9	2.7	2.4	3.3	6.7	4.5	5.6	8.4	7.5	6.2	16.1
Weathered gneissic	0.3	0.1	0.2	0.2	0.2	0.3	1.0	0.2	0.7	0.2	1.2	0.1	0.2	0.1	0.6	0.5	1.9
Schistose	1.3	0.4	0.2	0.3	0.2	0.1	0.4	0.1	0.5	0.5	0.6	0.3	0.1	0.6	0.4	1.1	0.2
Weathered schistose	0	0	TR	0	0	0	0.1	0	0	0	0.1	0	0	0	0	TR	0.2
Metasedimentary	1.2	0.9	1.1	3.0	2.8	3.9	2.2	1.5	1.2	2.2	5.9	4.3	5.4	8.5	8.0	7.6	17.5
Weathered metasedimentary	0	0.1	0	0	0	0	0	0.1	0	0.1	0	0.1	0	0	0.1	TR	1.6
Metagraywacke	0.6	1.3	1.0	1.6	1.1	2.8	1.0	1.4	0.7	1.9	2.7	1.2	1.3	1.7	0.4	1.3	4.6
Tillite	0	0	0.1	0.1	TR	0.1	TR	0	0	0.1	TR	TR	0.1	2.0	1.9	2.1	0
Quartzite	0.2	0.3	0.1	0.6	1.0	0.8	0.4	0	0.3	0.4	1.4	0.5	0.6	2.6	3.3	2.4	3.3

*See note on table 19.
+The letters "TR" designate the presence of trace amounts (<0.05%) of materials. The number "0" designates no material was present.

Table 17. Weight percent of each rock type passing a 3/8-inch and retained on a #4-mesh square aperture sieve.+

	Sample number																
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15	*
Sedimentary Rocks																	
Dolomite	52.1	59.6	54.5	38.1	50.6	50.1	45.2	55.8	60.2	29.0	22.5	36.4	28.5	15.4	19.8	17.9	0.7
Laminated dolomite	1.9	0.8	1.3	1.5	2.0	0.8	1.0	1.5	1.6	0.6	1.0	0.9	1.3	1.4	1.6	0.6	0
Silty dolomite	2.9	3.1	4.3	2.8	1.8	1.6	0.4	2.8	1.6	7.4	0.6	3.1	4.1	2.4	2.9	0.9	TR
Pyritic dolomite	0.2	0.8	1.4	0.2	0.5	0.2	0	1.4	0.4	0.3	0	0.2	0.2	0.1	0.1	0	0
Limestone	6.8	4.7	5.7	5.0	3.7	3.0	3.9	3.5	4.5	8.7	6.0	8.8	9.3	9.6	13.3	8.7	1.3
Cherty carbonate	2.9	3.8	6.3	5.7	4.9	4.0	4.9	9.1	7.0	4.6	3.7	5.6	6.5	6.7	7.5	7.3	0.8
Chert	9.0	6.8	8.5	23.7	17.2	20.6	22.4	9.6	7.2	15.9	18.6	14.2	15.8	20.4	15.7	21.1	15.9
Weathered carbonate	6.9	3.4	3.3	4.6	4.7	2.4	5.1	3.5	4.2	9.8	7.3	5.9	5.9	1.7	2.1	2.2	0.3
Ironstone	0.6	0.8	0.4	0.1	TR	TR	TR	0.1	0.2	1.8	0.3	2.1	1.1	0.5	0.6	0.3	1.2
Shale	0.2	0.1	0.3	0.2	0.1	0.1	0	0.2	TR	1.1	TR	0.6	0.6	0.7	1.2	0.4	TR
Sandstone-siltstone	3.7	2.7	3.3	3.0	1.9	2.6	3.5	2.1	3.9	6.0	8.3	4.0	4.0	7.8	6.0	11.1	0.8
Conglomerate	TR	TR	TR	0	TR	TR	0.1	0	TR	0.8	0.1	0.2	0.5	0.2	0.2	0.1	0
Igneous Rocks																	
Mafic	4.1	5.1	2.7	1.7	2.0	3.1	1.8	2.6	1.2	2.66	2.9	3.2	2.6	5.9	5.8	2.9	6.2
Weathered mafic	0.7	0.5	0.5	0.3	0.1	0.1	0.3	0.4	0.7	0.3	0.4	0.4	0.3	0.2	0.2	0.4	0.8
Coarse felsic	0.7	0.2	0.4	0.3	0.1	0.2	0.2	0.3	0.2	0.3	0.5	0.3	0.3	0.3	0.2	0.5	3.1
Weathered coarse felsic	0.1	TR	TR	0	0	0	0	TR	TR	TR	0.2	TR	TR	TR	0	0.1	0.2
Fine felsic	0.3	0.4	0.4	0.4	0.5	0.5	0.6	0.4	0.3	0.2	4.3	0.7	1.9	0.2	TR	0.4	8.2
Weathered fine felsic	0	0	0	0	TR	0	0	0	0	0	0	0	TR	0	0	TR	0.1
Massive quartz	0.2	0.2	0.1	1.7	1.2	0.4	2.0	0.2	0.1	2.5	4.0	1.4	3.1	2.5	1.2	3.0	5.7
Metamorphic Rocks																	
Gneissic	2.5	3.8	2.9	3.8	3.3	4.4	3.5	3.2	3.3	3.1	6.9	4.7	4.4	8.4	7.7	6.7	20.4
Weathered gneissic	0.3	0.4	0.4	0.7	0.4	0.2	0.5	0.3	0.4	0.4	1.5	0.3	0.5	0.6	0.7	1.2	3.3
Schistose	0.9	0.4	0.3	0.3	0.1	0.1	0.4	0.1	0.4	0.4	1.1	0.3	0.3	0.5	0.2	0.9	0.5
Weathered schistose	0.1	TR	0.1	TR	0	0	TR	TR	0.1	TR	0.1	TR	TR	0	TR	0.1	TR
Metasedimentary	1.5	1.5	1.5	3.7	3.2	2.9	2.9	1.6	1.0	2.5	6.6	4.6	6.2	9.1	8.0	8.4	18.7
Weathered metasedimentary	TR	0	0	TR	TR	0	0	0	0	0	0	TR	TR	TR	TR	TR	1.5
Metagraywacke	1.1	1.1	1.1	1.6	1.0	1.9	1.2	1.3	1.0	1.1	2.7	1.3	1.6	1.0	0.9	1.3	5.9
Tillite	0	0	TR	TR	0	TR	TR	0	TR	0.1	TR	0.2	0.1	1.7	1.6	2.1	0.1
Quartzite	0.1	0.1	0.1	0.4	0.4	0.8	0.4	0.3	0.1	0.4	0.7	0.7	0.7	2.6	2.2	1.3	3.9

*See note on table 19.

+The letters "TR" designate the presence of trace amounts (<0.05%) of material. The number "0" designates no material was present.

Table 18. Total weight percent of each rock type found in the 4 size ranges (tables 14, 15, 16, and 17) in the 60-pound gravel samples studied in Phase II.

	Sample number																
	1	2	3	4	5a	5b	6	7	8	9	10	11	12	13	14	15	*
Sedimentary Rocks																	
Dolomite	59.7	61.1	56.3	41.5	52.1	47.1	49.1	57.6	62.2	32.0	21.3	34.7	28.6	15.2	19.6	20.2	1.6
Laminated dolomite	3.5	2.8	2.5	2.8	2.1	1.2	1.4	1.8	3.0	1.3	1.8	1.6	1.8	1.9	2.5	1.3	TR
Silty dolomite	1.6	2.1	3.3	2.7	1.9	1.6	0.4	2.1	0.8	6.2	0.9	3.0	3.0	2.6	2.3	0.7	0.1
Pyritic dolomite	1.3	1.1	2.7	0.3	0.7	0.8	0	1.5	0.3	0.4	0	0.3	0.5	0.1	0.2	0	TR
Limestone	5.1	3.9	4.4	3.6	3.1	2.3	3.2	2.7	4.3	7.7	6.1	8.1	9.7	9.4	10.9	9.4	1.8
Cherty carbonate	4.5	4.6	7.4	7.2	4.8	4.7	5.3	10.1	6.2	6.1	3.9	8.2	7.2	9.4	8.6	6.7	2.3
Chert	5.2	5.9	7.5	20.3	17.2	19.6	18.3	9.7	6.5	15.0	21.1	14.4	15.6	19.0	15.0	21.4	21.7
Weathered carbonate	5.1	2.9	3.2	4.4	3.2	2.1	7.0	4.0	4.6	8.5	6.6	4.9	5.7	2.0	2.3	2.1	0.5
Ironstone	0.5	0.6	0.3	0.1	TR	TR	TR	0.1	0.1	1.5	0.2	1.4	0.8	0.4	0.4	0.2	1.4
Shale	0.1	0.3	0.3	0.1	0.1	0.1	TR	0.1	TR	0.7	TR	0.5	0.4	0.6	1.3	0.1	TR
Sandstone-siltstone	2.9	2.1	2.7	2.8	2.0	2.4	3.2	1.6	2.9	5.7	7.1	4.2	4.0	5.9	5.2	8.2	1.3
Conglomerate	TR	0.1	TR	0	TR	TR	TR	0	TR	0.5	0.2	0.1	0.3	0.3	0.3	0.1	TR
Igneous Rocks																	
Mafic	3.9	5.3	2.5	2.2	1.8	4.2	1.7	1.9	1.6	3.1	2.4	4.0	4.0	5.8	6.1	4.1	4.7
Weathered mafic	0.4	0.5	0.3	0.2	0.1	0.1	0.3	0.2	0.6	0.4	0.6	0.2	0.2	0.3	0.2	0.5	0.5
Coarse felsic	0.3	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.5	0.4	0.4	0.3	0.2	0.2	2.0
Weathered coarse felsic	TR	TR	TR	TR	TR	0	0	TR	TR	TR	0.1	TR	TR	TR	0	0.1	0.1
Fine felsic	0.4	0.4	0.3	0.5	0.5	0.8	0.6	0.4	0.3	0.2	5.2	1.0	2.1	0.1	0.1	0.3	9.6
Weathered fine felsic	0	0	0	0	TR	0	0	TR	0	0	0	0	TR	TR	0.2	TR	0.1
Massive quartz	TR	0.1	0.1	0.9	0.7	0.3	1.0	0.1	0.1	1.5	3.1	0.8	2.1	1.5	0.7	1.6	3.4
Metamorphic Rocks																	
Gneissic	2.1	3.5	2.8	4.3	3.7	4.8	3.1	2.5	3.2	3.2	7.7	5.0	5.5	8.8	8.6	7.1	19.6
Weathered gneissic	0.2	0.2	0.2	0.4	0.3	0.2	0.4	0.2	0.5	0.3	1.3	0.2	0.3	0.5	0.5	0.7	2.1
Schistose	1.1	0.4	0.2	0.3	0.2	0.2	0.5	0.1	0.5	0.4	0.7	0.3	0.1	0.5	0.2	1.1	0.3
Weathered schistose	TR	TR	TR	TR	0	0	0.1	TR	TR	TR	TR	TR	TR	TR	TR	0.1	0.2
Metasedimentary	1.1	1.3	1.4	3.1	2.9	4.0	2.5	1.6	1.0	3.1	5.7	4.9	6.0	9.1	8.7	8.3	17.6
Weathered metasedimentary	TR	TR	0	TR	TR	0	0	TR	0	TR	0	TR	TR	TR	0.1	TR	1.1
Metagraywacke	0.8	1.0	1.1	1.2	1.3	2.2	0.8	1.3	0.8	1.4	2.3	1.3	1.2	1.1	0.8	1.3	4.5
Tillite	0	0	TR	TR	0.1	0.1	TR	0	TR	0.2	0.1	0.1	0.1	1.9	2.1	2.1	TR
Quartzite	TR	0.2	0.1	0.5	0.8	1.0	0.8	0.1	0.2	0.3	1.2	0.6	0.8	2.9	2.9	2.0	3.6

*See note on table 19.

Table 19. Summary of weight percent data for rock types identified in the study samples (table 18) and corresponding geologic names of deposits and geographic names where samples were obtained (figs. 7, 8, and 9).

DIVISIONS OF GEOLOGIC TIME / Divisions of rock stratigraphy / Geographic locations	Sample no.	Rock Types								
		Sedimentary rocks								
		Dolo-mite	Lime-stone	Weathered carbonate rocks	Chert	Sandstone-siltstone	Other sedimentary rocks	Iron-stone	Igneous and metamorphic rocks	Weathered igneous and metamorphic rocks
QUATERNARY SYSTEM PLEISTOCENE SERIES WISCONSINAN STAGE										
Henry Formation (outwash deposits)										
Batavia Member (outwash plains)										
McHenry County	1	66.1	5.1	5.1	5.2	2.9	4.6	0.5	9.7	0.6
	2	67.1	3.9	2.9	5.9	2.1	5.0	0.6	12.6	0.7
	3	64.8	4.4	3.2	7.5	2.7	7.7	0.3	8.8	0.5
Mackinaw Member (valley trains)										
Rock River	4	47.3	3.6	4.4	20.3	2.8	7.3	0.1	13.3	0.6
	5a	56.8	3.1	3.2	17.2	2.0	4.9	TR	12.3	0.4
	5b	50.7	2.3	2.1	19.6	2.4	4.8	TR	17.8	0.3
	6	50.9	3.2	7.0	18.3	3.2	5.3	TR	11.3	0.8
Fox River	7	63.0	2.7	4.0	9.7	1.6	10.2	0.1	8.2	0.4
	8	66.3	4.3	4.6	6.5	2.9	6.2	0.1	8.0	1.1
Kickapoo Creek	9	39.9	7.7	8.5	15.0	5.7	7.3	1.5	13.6	0.7
Illinois River	10	24.0	6.1	6.6	21.1	7.1	4.1	0.2	28.9	2.0
	11	39.6	8.1	4.9	14.4	4.2	8.8	1.4	18.4	0.4
	12	33.9	9.7	5.7	15.6	4.0	7.9	0.8	22.3	0.5
Wabash River	13	19.8	9.4	2.0	19.0	5.9	10.3	0.4	32.0	0.8
	14	24.6	10.9	2.3	15.0	5.2	10.2	0.4	30.4	1.0
	15	22.2	9.4	2.1	21.4	8.2	6.9	0.2	28.1	1.4
Mississippi River	*	1.7	1.8	0.5	21.7	1.3	2.3	1.4	65.3	4.1

*Sample was obtained from product stockpile for rock type data only; it was not subjected to freeze-thaw or other quality tests.

deposits. All other samples are from valley-train deposits that contain abundant chert (15% to 22%), with the higher amounts tending to occur further downstream, or at greater distances from the glacial-age ice fronts (figs. 7, 8, and 9). These trends are probably fairly representative of the respective deposits, but additional data would certainly help substantiate them. For example, the study of only three samples from such large deposits as the McHenry County outwash plains may not properly define the full range of variability of the rock types in these deposits. Table 19 indicates that within each gravel production area the weight percent of several rock types varies widely; for instance, in the Illinois River valley-train deposits dolomite content varies from 24.0 to 39.6 percent and ironstone from 0.2 to 1.4 percent. Dolomite content is fairly distinct in each valley train system; it ranges from 63 to 69 percent in the Fox, from 47 to 57 percent in the Rock, from 24 to 40 percent in the Illinois, from 22 to 25 percent in the Wabash, to just 2 percent in the one Mississippi River valley sample. The igneous and metamorphic rock contents (including weathered varieties) in the samples from the valley trains range from 9 percent in the Fox, 12 to 18 percent in the Rock, 19 to 30 percent in the Illinois, 30 to 33 percent in the Wabash, and 69 percent in the Mississippi River valley sample.

There are few, if any, indications that a certain rock type is always more abundant in a certain particle-size range. However, there are some general trends: dolomite and a few other rock types tend to be more abundant in the coarser sizes; chert and several other rock types tend to be more abundant in the finer sizes; and several other rock types such as silty dolomite show no apparent trend.

Cracks and popouts

The surficial deterioration features on the freeze-thaw test beams containing the Phase II individual and rock-type groups (table 13) were described, using the same form (fig. 14) as was used for the Phase I samples. Table 20 includes the total number of pebbles found in popouts on the surface of these beams. The chert-free gravel column on table 20 represents the freeze-thaw testing of 60 pounds of gravel, from which the chert fraction had been removed. These samples were tested in order to see how much expansion would occur using gravel aggregate containing all rock types except chert.

The same rock types that caused popouts in the Phase I test beams caused popouts in Phase II beams. Beams made with chert (group 1, table 13) contained more pebbles in popouts than any other individual rock type except for ironstone in a couple of sets of group 5 test beams (table 20). For rock groups 2, 3, and 4, the number of pebbles in popouts is very low. Some of the popouts in group 2 are probably caused by borderline weathered carbonate rather than dolomite pebbles. Nearly every popout in group 3 contained a cherty carbonate pebble in which the cherty portion of the pebble was fractured (table 20). No popouts were found in the test beams containing igneous and metamorphic rock types (group 4).

Group 5 and chert-free test beams (table 20) commonly contain as many or more pebbles in popouts as the group 1 (chert) test beams. Ironstone pebbles are the most abundant rock type in these popouts, followed by weathered carbonate, silty dolomite, and sandstone-siltstone. That ironstone pebbles can

Table 20. Weight percentage of gravel, average freeze-thaw expansions, and numbers of pebbles in popouts in the three replicate test beams for each of the five rock-type groups (table 13).

Sample No.	Group 1 Wt. %	Group 1 Avg. % Exp.	Group 1 No. of Pebbles in Pop-outs	Group 2 Wt. %	Group 2 Avg. % Exp.	Group 2 No. of Pebbles in Pop-outs	Group 3 Wt. %	Group 3 Avg. % Exp.	Group 3 No. of Pebbles in Pop-outs	Group 4 Wt. %	Group 4 Avg. % Exp.	Group 4 No. of Pebbles in Pop-outs	Group 5 Wt. %	Group 5 Avg. % Exp.	Group 5 No. of Pebbles in Pop-outs	Chert Free Gravel Wt. %	Chert Free Gravel Avg. % Exp.	Chert Free Gravel No. of Pebbles In Pop-outs
1	5.8	0.010	12	66.9	0.002	5	*	*	-	*	*	-	*	*	-			
2	5.3	0.012	14	61.1	0.007	1	12.4	0.008	0	12.4	0.006	0	8.8	0.009	10			
3	7.5	0.019	11	56.3	0.006	0	17.0	0.005	0	8.9	0.003	0	10.4	0.009	12			
4	20.3	0.095	29	41.5	0.008	0	13.9	0.008	0	13.3	0.004	0	10.9	0.007	5			
5a	17.2	0.028	16	52.1	0.006	0	10.7	0.004	0	12.2	0.006	0	7.7	0.006	2	100	0.015	4
5b	19.6	0.020	17	47.1	0.007	1	9.0	0.008	2	17.9	0.005	0	6.4	0.008	0	100	0.005	1
6	21.3	0.066	27	57.3	0.010	3	*	*	-	*	*	-	*	*	-			
7	9.7	0.028	21	57.6	0.005	0	16.2	0.009	1	8.3	0.004	0	8.3	0.006	7			
8	7.2	0.013	13	69.1	0.003	0	*	*	-	*	*	-	*	*	-			
9	15.0	0.024	30	32.0	0.004	0	15.5	0.006	5	13.6	0.007	0	23.9	0.025	36			
10	24.2	0.044	14	24.4	0.008	2	*	*	-	*	*	-	*	*	-			
11	14.4	0.040	24	34.7	0.007	0	18.2	0.010	0	18.3	0.006	0	14.4	0.015	28	100	0.026	30
12	15.6	0.025	18	28.6	0.008	1	19.1	0.009	3	21.8	0.007	0	14.8	0.011	20	100	0.017	11
13	19.0	0.026	29	15.2	0.009	1	20.8	0.013	2	32.1	0.003	0	12.9	0.013	11	100	0.004+	4
14	15.0	0.068	19	19.6	0.009	0	22.2	0.011	1	30.4	0.009	0	12.7	0.012	16	100	0.018	14
15	27.4	0.084	23	25.9	0.004	1	*	*	-	*	*	-	*	*	-			

*Estimated average expansion for one set of test beams, assuming all rock types in Groups 3, 4, and 5 had been cast together: sample 1 = 0.009, sample 6 = 0.008, sample 8 = 0.010, sample 10 = 0.024, and sample 15 = 0.012.

+Estimated average expansion, due to loose measuring pins.

- = No value available.

generate internal disruptive forces that can break test beams (fig. 4) and cause popouts is illustrated in figure 27, in which cracks radiate toward the surface of a beam from an ironstone pebble, through the dolomite pebble on the left and around the dolomite pebble on the right, forming an incipient popout. Like most chert pebbles found in popouts, ironstone pebbles probably generate forces sufficient to cause expansion when located deeper within the test beams.

Popouts in chert (group 1) test beams expose near-surface deleterious cherts. Basic types of cherts that cause popouts (fig. 28) and surface cracks (fig. 29) and a small number that appear to be inert (fig. 28), were characterized in this study. These chert pebbles were divided into three categories (porous porcelaneous chert, brittle porcelaneous chert, and waxy chert) based on their physical appearance (table 21). Included in this table are the second set of chert (group 1) beams from samples 5a, 5b, 11, 12, and 14 in which chert pebbles had been separated from the gravel samples in order to test the freeze-thaw performance of chert-free gravel. The three categories of chert are based on characteristics of internal broken pebble surfaces rather than the external pebble surfaces, because within popouts, internal surfaces of fractured pebbles are better exposed and relate more directly to the results of freeze-thaw forces. Luster, a property of light reflectance, and texture, a property of surface granularity, are much more important than color for distinguishing types of chert. Fractured chert pebbles are usually porcelaneous: that is, they have a relatively dull, earthy luster and the very fine, granular texture of unglazed porcelain. For this study porcelaneous cherts are subdivided into type I and type II on the basis of the degree of induration and porosity:

Type I: porcelaneous cherts are porous, punky and so incompletely indurated that they can be gouged with the hardness tool used for rock-type identification.

Type II: porcelaneous cherts are brittle, thoroughly indurated, very fine grained, much less porous than type I, and too hard to be gouged with the hardness tester, but may be scratched.

Type III: waxy, resinous, and vitreous cherts that that appears to be inert and are varicolored (usually ranging between shades of white, creamy-tan and gray), often translucent, extremely fine grained, cannot be scratched with the hardness tester, and break with a pronounced conchoidal fracture.

Table 21 shows that the most abundant type of chert found in popouts (per 3-beam set) is type II (brittle) chert with up to 20 occurrences. Type I chert (porous) is next in abundance with up to 12 occurrences in popouts. Very few type III cherts (up to two) are present in popouts, and many of them are probably not the cause of the popout, but were fractured or exposed (fig. 28) because of their proximity to type I and II cherts. Type I or II cherts are commonly found in the cores of popouts, and usually are shattered (fig. 28) into many splintery fragments. These characteristics illustrate the concentration of force involved in the generation of a popout. The intersecting deterioration cracks (fig. 29) on the surface of a chert test beam may mark the location of an expansive chert pebble below the surface.

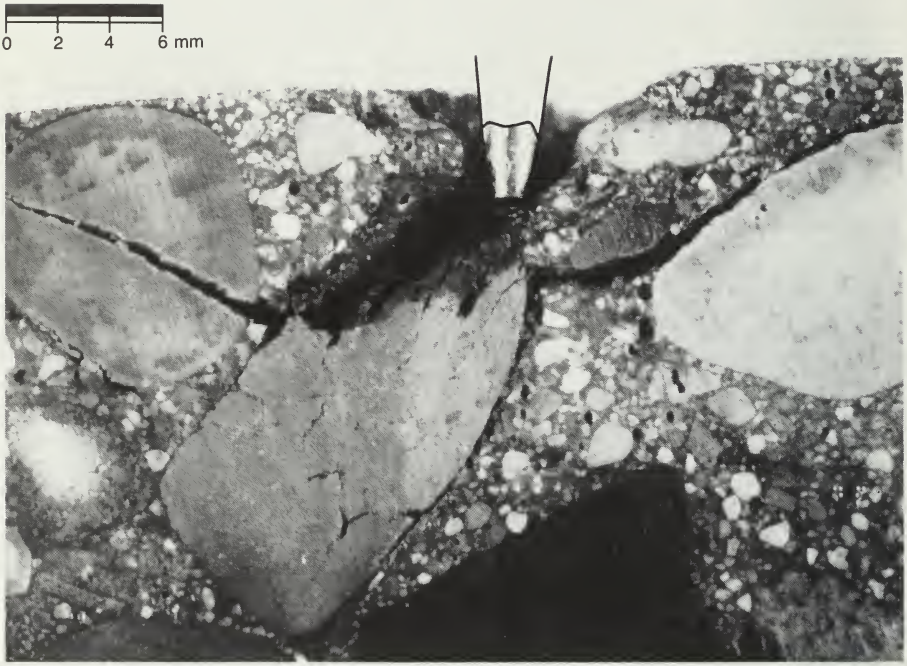


Figure 27. Cross section of an incipient popout with cracks radiating away from the ironstone pebble at the locus of the cracks (below pencil point) toward the test-beam surface.

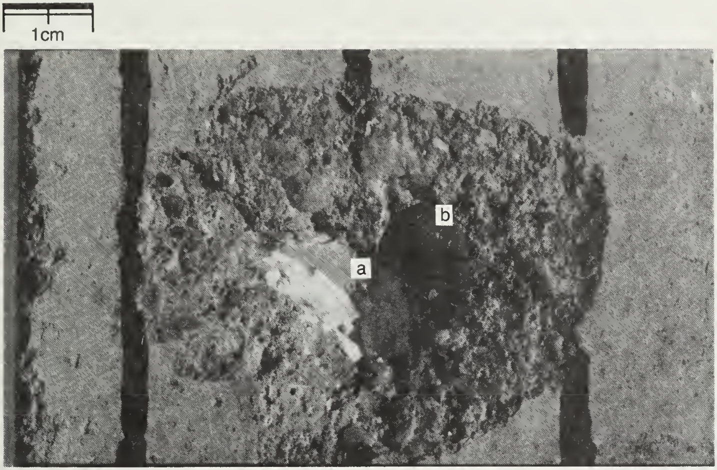


Figure 28. Chert pebbles in a popout on a chert (group 1) test beam. A type II shattered porcelaneous chert pebble at the core of the popout (a), and a type III intact, vitreous chert pebble (b). The black lines mark where the beam will be cut into slabs.

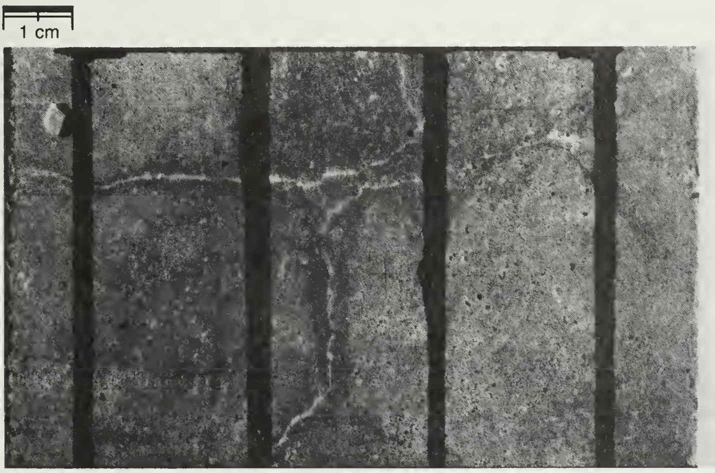


Figure 29. Intersecting deterioration cracks on the surface of a chert (group 1) test beam. The black lines mark where the beam will be cut into slabs.

Table 21. Classification of chert pebbles on the basis of their physical characteristics in popouts on the surfaces of chert test beams (group 1).**

Sample No.	Weight % Chert from 60-pound samples	Number of Cherts in Popouts (3-beam totals) Types I Porous	II Brittle	III Waxy	Total	Phase II Chert Avg. % Exp.
1	5.8	1	10	1	12	0.010
2	5.9	5	8	1	14	0.012
3	7.5	4	6	1	11	0.019
4	20.3	10	17	2	29	0.095
5a	17.2	4	12	0	16	0.028
5a (CH-2)*	17.8	10	15	1	26	0.029
5b	19.6	4	12	1	17	0.020
5b (CH-2)*	19.3	6	7	0	13	0.020
6	21.3	5	20	2	27	0.067
7	9.7	6	13	2	21	0.028
8	7.2	4	9	0	13	0.013
9	15.0	11	18	1	30	0.024
10	24.2	3	9	2	14	0.044
11	14.4	7	15	2	24	0.040
11 (CH-2)*	14.7	4	8	0	12	0.026
12	15.6	8	10	0	18	0.024
12 (CH-2)*	16.5	9	9	0	18	0.034
13	19.0	12	17	0	29	0.026
14	15.0	8	11	0	19	0.069
14 (CH-2)*	15.2	4	5	0	9	0.028+
15	27.4	6	17	0	23	0.087

*NOTE: CH-2 = second round of testing chert test beams (group 1).
+anomalously low value.
**Included are the weight percentages of chert pebbles separated per sample and the respective percent expansion per set of test beams.

It should be stressed that it was not in the scope of this study to characterize all of the varieties of chert found in the study samples. The complexity of such a study was shown by Kneller et al. (1968) who attempted a characterization of some cherts in coarse aggregates used by Ohio concrete producers. However, since cherts are apparently a major cause of freeze-thaw expansion in Illinois concrete quality gravels, further study of them could be very useful in determining what varieties of cherts do and do not cause freeze-thaw expansion.

Statistical analyses

As in Phase I, SAS General Linear Models (GLM) simple regression analyses were used first to test the relationship of the rock type groups to expansion. The weight percent of material in each of the five groups of rock types (tables 13 and 20) was compared to the average expansion values of the freeze-thaw test-beams of the 16 samples (groups 1 and 2) or 11 samples (groups 3, 4, and 5). The results of the analyses are summarized in table 22.

Table 22. Summary of simple regression analyses obtained in Phase II using SAS General Linear Models procedure to individually evaluate the data on the 5 groups of rock types (tables 13 and 20) by comparing the weight percent of material in each group with their respective freeze-thaw expansions (Phase II data).*

Rock-type Group	No. of Samples	Slope	F Value	R-Square	Prob > F
Chert (1)	16	+	13	0.48	0.0028
Dolomite (2)	16	-	4	0.21	0.0772
3	11	+	6	0.41	0.0327
4	11	+	1	0.09	0.3601
5	11	+	72	0.89	0.0001

*Both chert (group 1) and dolomite (group 2) have degrees of freedom for the F test of 1 and 14. Groups 3, 4, and 5 have degrees of freedom for the F test of 1 and 9.

The F Value and R-Square values for Phase II chert (Group 1) data (table 22) are even higher than those for chert in Phase I (table 8), using either individual test beam data or averaged data from the triplicate sets of test beams. As with the Phase I chert data, the Prob > F values for Phase II chert data indicate that the statistical test results are highly significant. The R-Square indicates that about half of the variability in the expansion data for the chert test beams can be explained by a linear relationship with the weight percentages of chert in the samples. This strengthens the tentative conclusion in Phase I that chert is related to expansion. The variability of the chert data is shown in figure 30, in which very low test-beam expansion

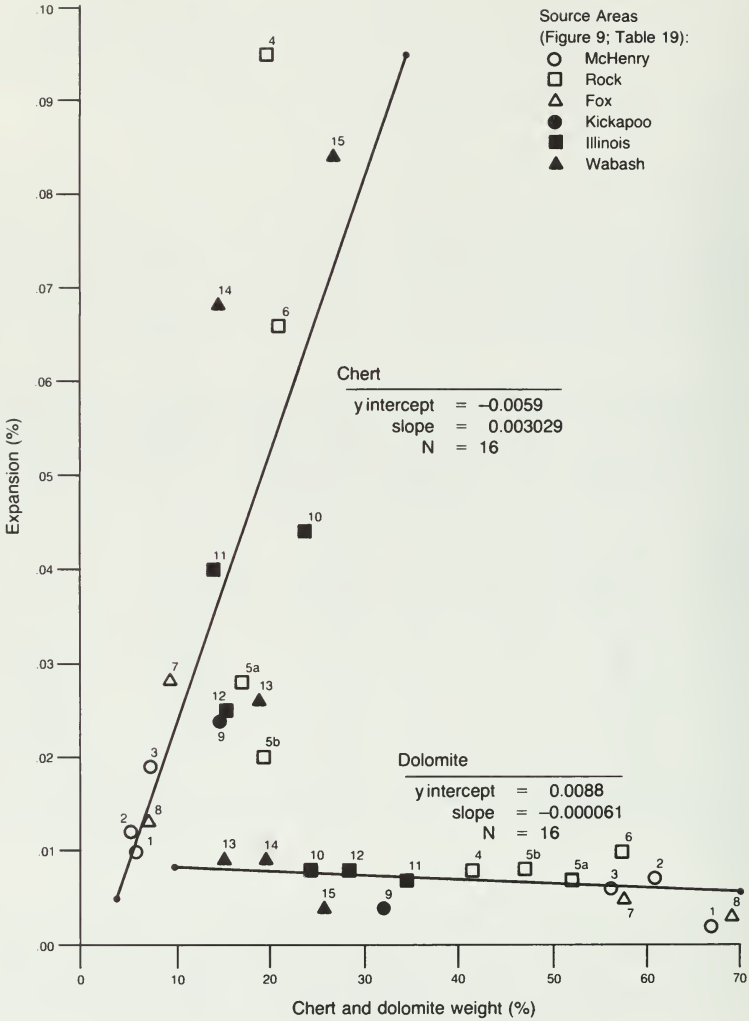


Figure 30. Comparison of chert (group 1) and dolomite (group 2) with the average weight percentage of each plotted against the average percent expansion of the respective triplicate sets of test beams (tables 18 and 20). Each point is identified by its sample number and source area (fig. 9; table 19).

percentages (about 0.02%) are associated with a wide range (about 8% to 20%) of chert content. Also, high chert content (about 20%) is associated with a wide range of expansion percentages (about 0.02% to 0.095%) in the test beams. Thus, although the positive slope of the regression line (table 22; fig. 30) certainly suggests that weight percent chert is directly related to expansion, the regression line should not be used to predict a certain percentage expansion from a given weight percent chert.

As with Phase I data, much of the variability of the Phase II chert data can be explained by the nonuniform locations of highly expansive (often low specific gravity) chert pebbles within critical portions of the test beams. Visual and statistical analysis of chert content data and the number of chert pebbles found in popouts compared to test-beam expansion (figs. 28 and 31; table 21) showed that chert content data (table 22) was much more closely related to expansion than chert popout data. The strength of the relationship between chert content and freeze-thaw expansion is probably reduced by the variable nature of the physical properties of the chert and the variable location of certain highly expansive chert pebbles in the test beams. Highly expansive chert pebbles that happen to be near test-beam surfaces often pop out instead of fully contributing to test-beam expansion.

Dolomite (group 2) data (table 22; fig. 30) once again did not correlate with increased freeze-thaw expansion. These dolomite (Phase II) data are less significant with respect to F Value, R-Square, and Prob > F than were Phase I dolomite data. The weight percent dolomite data show no appreciable relationship to expansion. The neutral effect of dolomite in the gravel samples can be further demonstrated by comparing the average freeze-thaw expansion of 0.0066 percent for 48 Phase II dolomite (group 2) gravel test-beams of with that of 0.0060 percent for 83 experimental-control test-beams. The coarse aggregate in the control test-beams was nonexpansive crushed dolomite (quarry rock).

The simple regression analyses values in table 22 show that of the five groups, group 4 is the least related to expansion, as indicated by its very low F Value, R-Square, and Prob > F in the not significant range (>0.1). Multiple regression analysis of group 4 data determined that none of the rock types in the group met the 0.15 significance level for entry into the model, indicating that none of the rock types in group 4 had a relationship to group 4 test-beam expansion that was significant at the 85 percent confidence level. Since metagraywacke is in group 4, this analysis suggests that the inclusion of metagraywacke in Model B (table 9) as a possible cause of expansion may not be justified.

The simple regression analysis of group 3 data indicated that this group may contribute slightly to expansion (table 22). Multiple regression analysis of the individual weight-percent rock-type data in group 3 determined that a model consisting of cherty carbonate and pyritic dolomite is significant at the 85 percent confidence level. The model has degrees of freedom for the F test of 2 and 8, an F Value of 7, and an R-Square of 0.64. The Prob > F value of 0.0173 indicates that the relationship of the model to expansion model is clearly significant. Thus even though neither of these rock types stood out in Model A or B (table 9) when compared to all the rock types, they may cause sufficient expansion to be significant when tested only with group 3 rock types. Since limestone was not identified as being closely related to freeze-

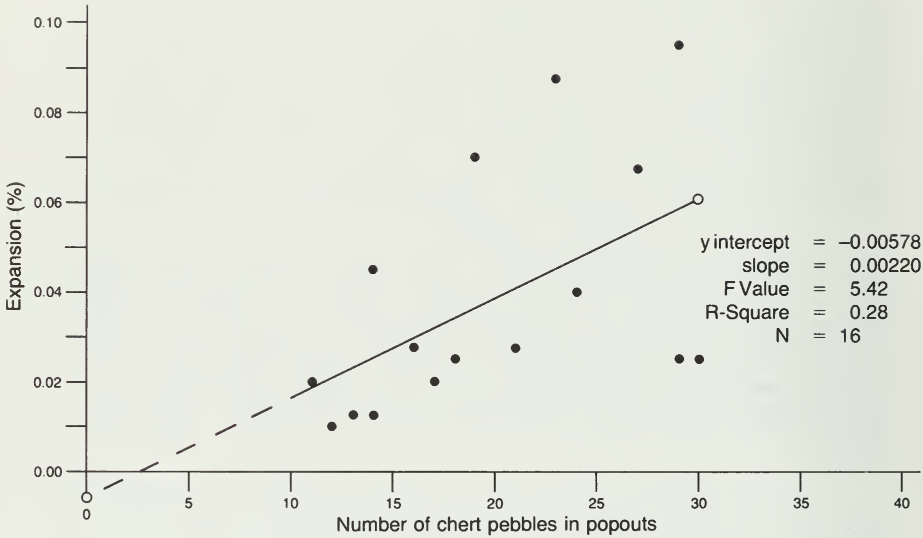


Figure 31. Total numbers of chert pebbles found in popouts in each triplicate set of chert (group 1) test beams, plotted against their respective average percent expansion.

thaw expansion by this multiple regression model, the indication by the Phase I data (table 8) that it may have caused some expansion is not supported. However, this does not mean that other samples with higher weight-percent limestone would not experience an increase in expansion, it only means that the low weight percent of limestone found in the study samples did not cause significant expansion.

A surprisingly strong relationship of group 5 rock types (table 13) with expansion (table 22) is indicated by the simple regression analysis. The F Value and R-Square numbers for group 5 are extremely high compared to the other groups. With degrees of freedom for the F test of 1 and 9, the Prob > F is in the very highly significant range (<0.001). Thus the R-Square value indicates that about 90 percent of the variability in the group 5 test-beam expansion data can be explained by a linear relationship with the group 5 weight-percent data. However, no statistical method has been developed during this study to show whether group 5 or group 1 (chert) is the more significant cause of expansion. Data in table 20 show that in sample 11, which contains similar amounts of chert and group 5 material (14.4%), expansion of chert is greater (0.040%) than expansion of group 5 material (0.015%). Such observations clearly suggest that chert causes more test-beam expansion than group 5 rock types.

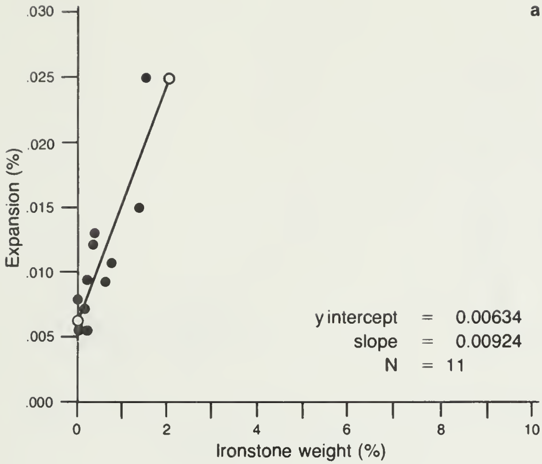
A comparison of the simple regression analyses of chert (group 1) content and expansion data with that of group 5 (table 22) indicates that even though chert causes greater expansion than group 5, the chert expansion data are more variable (lower R-Square) than that of group 5 (higher R-Square). This may be explained if it is recognized that the chert (group 1) test beams contained both expansive and nonexpansive chert pebbles in unknown proportions. The average expansion value of each triplicate set of test beams would be expected to vary, depending on the ratio of expansive to nonexpansive chert pebbles in the test beams. If there is a nearly continuous gradation from the most expansive to the least expansive chert pebbles, then even greater variability will be introduced.

The weight-percent data for each of the twelve rock types in group 5 were analysed individually versus the average expansion data from each triplicate set of group 5 test beams, using the GLM simple regression procedure. Rock types with the six highest F Value and R-Square values in group 5 are listed in order in table 23. The Prob > F values for these six rock types are in the range of very highly significant (<0.001) for ironstone and silty dolomite, highly significant (<0.01) for conglomerate and sandstone-siltstone, and clearly significant (<0.05) for weathered carbonate and shale. These high values and the GLM graphs of ironstone, silty dolomite, conglomerate, sandstone-siltstone, weathered carbonate and shale (figures 32 a, b, c, d, e, and f respectively) all give the appearance of relating well to expansion. However, their relative importance with respect to expansion data is difficult to evaluate because of the very small amounts of material (for some rock types) and very low expansions involved. It is assumed that the very high F Value and R-Square values, and very low Prob > F values for ironstone and silty dolomite indicate that they may be responsible for more expansion than are the other four rock types. The analyses of the data on the other rock types in group 5 (table 13) show F values below 5 indicating they have a very poor relationship with expansion; thus, at the low contents they exhibit in

Table 23. Summary of simple regression analyses on the six rock types most highly related to expansion in group 5, obtained using SAS General Linear Models procedure to evaluate the weight-percent data of all rock types in group 5 versus the average percent expansion of each triplicate set of test beams (tables 13, 18, and 20).*

Rock types in Group 5	No. of Samples	Slope	F Value	R-Square	Prob > F
Ironstone	11	+	33	0.78	0.0003
Silty dolomite	11	+	31	0.77	0.0004
Conglomerate	11	+	17	0.65	0.0026
sandstone-siltstone	11	+	15	0.62	0.0039
Weathered carbonate	11	+	8	0.47	0.0193
Shale	11	+	5	0.36	0.0494

*Degrees of freedom for the F test are 1 and 9.



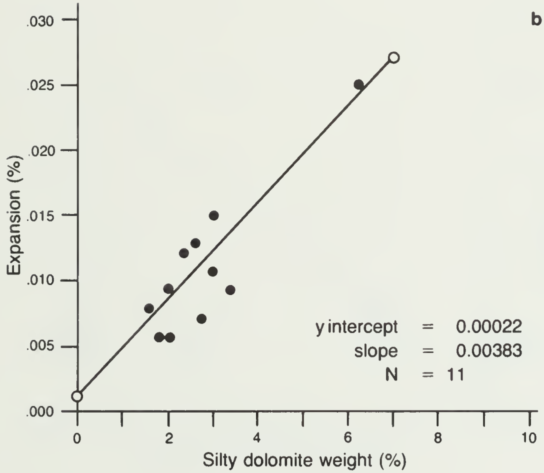
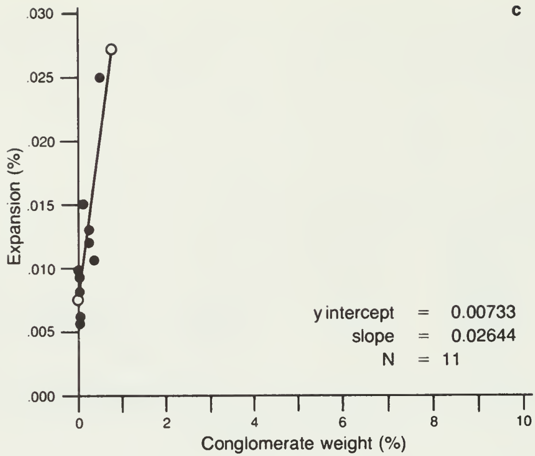
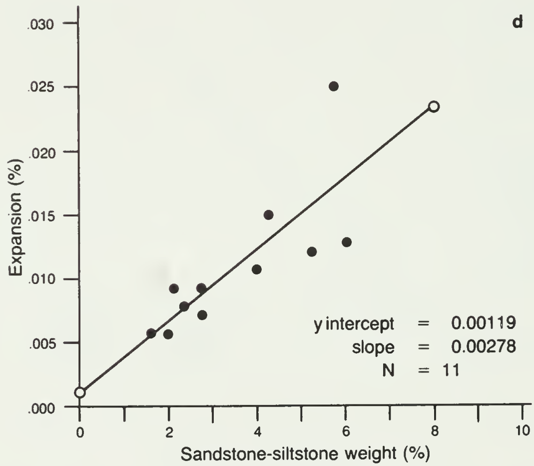
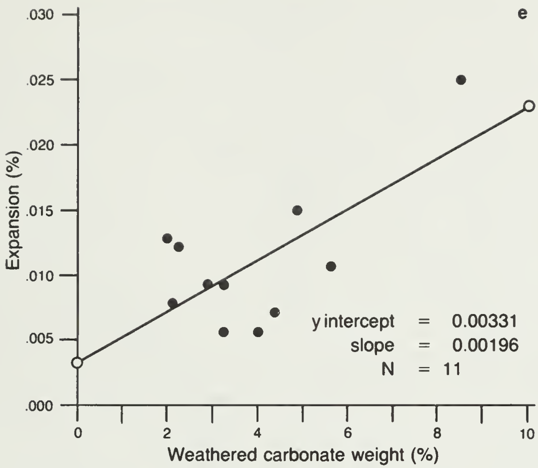
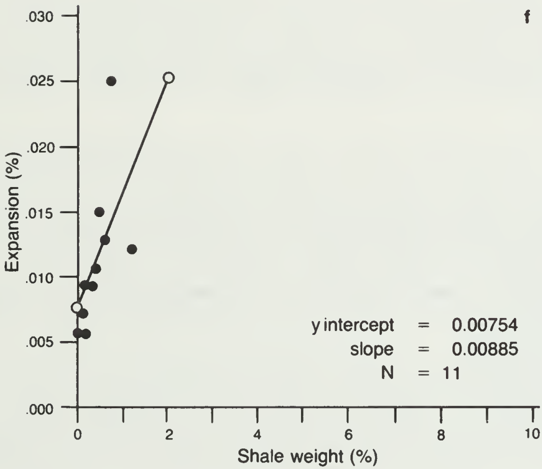


Figure 32. GLM simple regression graphs of the 6 rock types in group 5 most highly related to expansion (tables 13, 18, and 20); (a) ironstone, (b) silty dolomite, (c) conglomerate, (d) sandstone-siltstone, (e) weathered carbonate, and (f) shale. N is the number of samples.


c
.030
.025
.020
.015
.010
.005
.000
Expansion (%)
y intercept = 0.00733
slope = 0.02644
N = 11
0
2
4
6
8
10
Conglomerate weight (%)


d
.030
.025
.020
.015
.010
.005
.000
Expansion (%)
y intercept = 0.00119
slope = 0.00278
N = 11
0
2
4
6
8
10
Sandstone-siltstone weight (%)


e
.030
.025
.020
.015
.010
.005
.000
Expansion (%)
0
2
4
6
8
10
Weathered carbonate weight (%)
y intercept = 0.00331
slope = 0.00196
N = 11


f
.030
.025
.020
.015
.010
.005
.000
Expansion (%)
0
2
4
6
8
10
Shale weight (%)
y intercept = 0.00754
slope = 0.00885
N = 11

the study samples (tables 14, 15, 16, 17, and 18), they do not significantly contribute to increased freeze-thaw expansion.

The model resulting from multiple regression analyses (SAS Stepwise Regression multivariate procedure) of all twelve rock types in group 5 is shown in table 24. This model, consisting of five rock types, has the surprisingly high R-Square of 0.98, and is significant at the 85 percent confidence level. The model has a Prob > F (0.0004) in the very highly significant range. The rather low degrees of freedom for this model indicate that caution should be used when interpreting the analysis; we may not have had enough data to justify the extremely high significance of the relationship to expansion that the stepwise regression places on the model and its members. Data from only 11 samples are included in this analysis, and many of the rock types in group 5 are absent or occur only in trace amounts in several samples (table 18). However, ironstone and silty dolomite have much higher F Value and much lower Prob > F numbers (table 24) than the other three rock types, implying that they probably have the strongest effect on expansion of all group 5 rock types. Previous analyses (table 9) and observations concerning cracks (figs. 4 and 27) and popouts (table 20) indicate that ironstone is probably a more expansive rock type than silty dolomite. Pebbles of weathered carbonate rock were noted in popouts and its inclusion in the model of group 5 rock types causing significant expansion is reasonable. The exclusion of conglomerate, sandstone-siltsone and shale from the same model is suprising and they should still be suspected of causing expansion. The inclusion of weathered schistose and weathered fine felsic, two of the rarest rock types in the study samples (table 18), is unexpected, and not considered highly important. Their presence in the model only raises the R-Square value from 0.96 to 0.98, indicating their impact is small. Furthermore, significant amounts of any weathered rock type in coarse aggregates used in Portland cement concrete should be considered suspect since weathering processes typically weaken rocks and increase their porosity and permeability, which may make them susceptable to freeze-thaw expansion. In general, other gravel samples that contain more of these group 5 rock types than was present in the study samples could cause more expansion.

In terms of determining which rock types are most responsible for freeze-thaw expansion, the statistical analyses indicate that the Phase II rock type and expansion data tend to support the Phase I rock type and expansion data. The multiple regression analyses appear more definitive than the simple regression analyses of either Phase I or II data. However, caution must be used not to overemphasize the results, especially in the case of group 5, considering the small number of samples analysed, the small amounts present of some critical rock types, the small expansion values, and the small range of those expansion values.

In summary, the Phase II data analyses indicate that chert (group 1) is more strongly related to expansion than is any other rock type. Dolomite (group 2) is neutral with respect to expansion and appears unaffected by the freeze-thaw test. Of the group 3 rock types, cherty dolomite and pyritic dolomite should be considered suspect. The igneous and metamorphic rocks in group 4, including metagraywacke, do not contribute to expansion. Among group 5 rock types, ironstone and silty dolomite probably cause significant expansion, and conglomerate, sandstone-siltstone, weathered carbonate, shale, and weathered rocks in general should be considered suspect. The high

Table 24. Summary of multiple regression analyses obtained using the SAS Stepwise Regression procedure to identify the model containing the rock types in group 5 (tables 13, 18, and 20) that have most significant relationship with the average expansion of each triplicate set of test beams.*

Rock types in group 5	No. of samples	F Value	Prob > F
Silty dolomite	11	39	0.0019
Ironstone	11	35	0.0016
Weathered carbonate	11	18	0.0084
Weathered schistose	11	9	0.0289
Weathered fine felsic	11	5	0.0807

*Degrees of freedom for the F test are 5 and 5.

statistical significance between test-beam expansion and these group 5 rock types may be misleading, as described previously.

APPLICATIONS OF ROCK-TYPE DATA TO PIT OPERATIONS

Introduction

Information generated during this project may be applicable to some specific problems being encountered by the construction aggregate industry. For example, rock type information may be useful in selecting processing equipment that will enhance product quality and in planning the excavation of a gravel deposit to optimize the volume and quality of aggregate products.

A possible effect of processing

Chert pebble content and expansion data (tables 18 and 20; fig. 30), plus other information on the pits from which the four Rock River valley processed gravel samples were obtained, indicate that the use of certain processing methods may improve gravel quality. All four of these samples contained about 20 percent chert, but the expansion of test beams containing these pebbles ranged from 0.020 to 0.095 percent (table 25). Factors within the sand and gravel deposits that probably contributed greatly to these differences in freeze-thaw test-beam expansion include differences in compositions of the gravels in distinct terrace systems in the valley, and downstream variations in particle-size distribution and in physical properties of the gravel-size material within the terraces. Other important factors included differences in processing methods at the respective gravel pits. Data in the following discussion is from tables 2, 3, 11, 18, and 25.

Since sample 4 was from a pit located much farther downstream than the other three, it may be that: (1) at the time glacial meltwater was depositing material in the valley the meltwater may not have been capable of carrying

Table 25. Data on the numbers and types of industrial rock-crushers used in processing the coarse-aggregate stockpiles from which the study samples were collected, plus data on chipped and broken pebbles, and the average percent expansion of the freeze-thaw test beams.

Sample No.	Crushers			Percent chipped or broken pebbles in the 1/2- to 3/4-inch size		Average percent expansion of test beams		
	No.	Types	Maximum opening of smallest (inches)	Dolomite	Chert	Phase I: Gravel containing all rock types	Phase II: Dolomite gravel	Phase II: Chert gravel
1	3	jaw, cone & roll	1	*	*	0.028[x]	0.002	0.010
2	3	jaw, cone & roll	1	45	25	0.016	0.007	0.012
3	3	cones	1	14	25	0.030	0.008	0.019
4	1	jaw	1 5/8	6	8	0.081	0.008	0.095
5a	2	jaw & roll	3/4	66	65	0.058+	0.007	0.028+
5b	1	vertical impactor	3/4	92	89	0.034+	0.007	0.020+
6	1	jaw	1 1/2	20	20	0.062	0.010	0.066
7	1	cone	1 7/8	7	9	0.062	0.005	0.028
8	1	cone	3/4	50	41	0.030	0.003	0.013
9	1	jaw	2 1/2	7	14	0.067	0.004	0.024
10	0	--	--	11	17	0.063	0.008	0.044
11	1	jaw (?)	2	22	16	0.089	0.007	0.033
12	1	jaw (?)	1 1/2	7	8	0.082	0.008	0.029+
13	0	--	--	4	11	0.067	0.009	0.030+
14	1	jaw (?)	1 1/2	25	14	0.066	0.009	0.048+
15	0	--	--	14	19	0.063	0.004	0.084

*Values not available.

+Average of six beams, all others are average of three beams.

[x]Includes one estimated expansion value.

much gravel that far downstream; (2) a significant portion of the gravel-size material carried that far may have been low specific gravity (<2.35) chert, since in a constant current, water can transport gravel that is lighter farther downstream than it can heavier gravel the same size; or (3) low specific gravity chert gravel may have been added to the meltwater stream at points farther downstream than the other locations. The stream of glacial meltwater that deposited the sand and gravel at the sample 4 location in a low terrace may also have been carrying a significantly different mixture of gravel-size chert than was deposited in the high terrace at the sample 5a, 5b, and 6 locations.

Samples 4 and 6 were from pits in which gravel is not abundant and most of the gravel-size material is less than 1 1/2 inches. Also, only the plus 1 1/2 inch sieve-size gravel is crushed (table 25). Thus, only a low percentage of the gravel particles is subjected to the high compressive force of the crushing process. The pit from which sample 4 was obtained contains even less gravel than that of sample 6, and the sample was subjected to the least amount of crushing (if any). Only 8 percent of the 3/4- to 1/2-inch chert in sample 4 was chipped or broken. Sample 4 also contains the largest amount (2.3%) of low specific gravity (<2.35) chert, and has the largest chert test-beam expansion (0.095 %) of all four Rock River valley samples. Sample 6 contains the next lowest amount of chipped or broken 3/4- to 1/2-inch chert (20%), the next largest amount (1.4%) of low specific gravity chert, and the second largest chert test-beam expansion (0.066%).

Of the Rock River valley samples, numbers 5a and 5b (from the same pit) are from a deposit where gravel-size material is significantly more abundant and coarser grained than in the deposits where samples 4 and 6 were collected. All of the pit-run gravel from which samples 5a and 5b were obtained was passed through the respective crushers, crushing the top-size to the less than 3/4-inch size. Sample 5a was processed through a jaw and roll crusher unit, resulting in the third lowest amount (65%) of chipped or broken 3/4- to 1/2-inch chert. It contains the third largest amount (1.2%) of low specific gravity chert, and the third largest chert test-beam expansion (0.028%). Sample 5b was processed through a vertical impact crusher, resulting in the highest (4th lowest) amount (89%) of chipped or broken 3/4- to 1/2-inch chert. It contains the lowest (4th largest) amount (1.0%) low specific gravity chert, and has the lowest (4th largest) chert test-beam expansion (0.020%), even though it contained 2.4 percent more total chert than did 5a. This study has shown that the amount of low specific gravity chert in the sample is more strongly related to test-beam expansion than is total chert content.

In summary, progressing from sample 4 to 6, to 5a and to 5b (remembering that all four samples contain about 20 percent chert): (1) gravel in the respective Rock River valley deposits becomes more abundant and coarser grained (except 5a and b, which are the same); (2) percentages of chipped or broken chert pebbles increase; and (3) percentages of low specific gravity (<2.35) chert decrease. Other physical properties that follow this trend are: (1) total deleterious materials decrease; (2) soft and unsound materials decrease; and (3) total popouts and chert popouts on Phase I test beams decrease (tables 2, 3, 11, and 18). It is significant for the above samples (table 25) expansion of the test beams containing all rock types (Phase I) as well as expansion of the chert test beams (Phase II) decrease in the same order.

The low expansion values of samples 5a and 5b may be related not only to the large percentage of crushed gravel they contain, but also to the crushing methods used to process them. It seems possible that the vertical impactor may have broken down a significantly greater amount of the low specific gravity chert in sample 5b, than did the jaw and roll crusher in sample 5a.

Since processed samples from the coarsest grained deposits contain the least expansive cherts, it may be that crushing tends to preferentially break down highly expansive cherts. For example, crushing may be successful in reducing the expansive chert content in deposits where brittle, easily fractured chert is abundant, but it may not work in the Wabash River valley train deposits where less brittle expansive rock types such as ironstone are also abundant (table 18). All factors relating to downstream changes in the physical properies of the gravel in the deposits have not been sufficiently evaluated, and the effectiveness of increased crushing and different types of crushers in a particular deposit has not been tested adequately. However, rock type information (such as is presented in this study) can help evaluate differences between gravel deposits and the effectiveness of different types of processing equipment.

Samples 7 and 8: A comparison

Samples 7 and 8 are from different pits that are only about one mile apart. Although they are from the same terrace in the valley-train deposits of the Fox River valley, sample 8 has a three beam average expansion value of 0.030 percent compared to 0.063 percent for sample 7 (table 25). This may be because sample 8 has less chert than sample 7 (table 18), and more broken particles of the abundant rock types than sample 7 (table 25). Sample 8 may have a lower chert content for two reasons: (1) sample 7 was produced from a 40-foot interval of sand and gravel, but sample 8 was produced from only the upper 15 feet of that interval, which may have contained significantly less chert than the average amount in the total interval; and (2) since sample 8 contained several times more broken particles than did sample 7, the upper 15 feet must have been much coarser grained than the average grain-size of the total interval. It is probable that the upper 15 feet of the deposit in which sample 8 originated was much coarser gravel than the same interval in the sample 7 deposit.

However, this explanation of the differences between samples 7 and 8 becomes complicated when data from IDOT tests conducted prior to the current study (table 10) are considered. In these earlier tests, results of freeze-thaw data from these two pits are reversed (that is, test beams made with gravel collected from the pit represented by sample 7 gave lower expansion values than those from the sample 8 site). This reversal was also found in IDOT's previous quality test data, where sample 7 had a lower chert content than sample 8.

The most likely reasons for this reversal of test data on gravel collected from these pits are horizontal and vertical variations in the lithologic compositions of the gravel deposit, and related variations in coarseness (particle-size distribution) of the deposit. Thus, samples collected during the past 2-year period probably came from material excavated from different portions of the deposit that vary signicantly in rock-type compositions and particle-size distributions.

These differences between samples 7 and 8 illustrate the potential value of rock type and other geologic studies of gravel pit sites to subdivide them into zones or facies on the basis of their fine-, medium- and coarse-gravel contents, and of their rock-type content. The sand and gravel can then be mined selectively, and only the coarsest and highest quality zones excavated for use as concrete aggregate products. For example, in some gravel deposits, chert and other deleterious rock types such as ironstones are concentrated near the bottom of the deposits. Knowledge of this situation in a pit would allow excavation plans to leave that material in place, so that it does not contaminate the overlying material and lower its quality. During another phase of excavation, the underlying material could be removed in a separate lift, for use in lower grade aggregate products.

CONCLUSIONS

Rock types identified in selected samples of gravel aggregates used in Portland cement concrete highways in Illinois were identified, and their relationship to IDOT freeze-thaw test data was evaluated. The overall conclusions are briefly stated below as "highlights," then described in more detail in the following sections.

Highlights of study findings

° The most expansive rock types in the gravels studied are chert, especially chert with a low specific gravity (<2.35), and to a lesser degree ironstone, along with silty dolomite and possibly weathered carbonate.

° Very small amounts of expansive pebbles can cause significant expansion in test beams, most notably low specific gravity (<2.35) chert ranging from 0.2 to 2.9 weight percent (table 11), and ironstone ranging from a trace to 1.5 weight percent (table 18).

° The variability in freeze-thaw expansion between test beams of the same sample, and between different samples from the same source is probably related to: (a) non-uniform positioning of expansive pebbles within the central core of the test beams; and (b) nonrepresentative amounts of all types of expansive pebbles in the portions of the samples that go into the individual test beams.

° The rock-type classification devised for this study is adequate for identifying those rock types in high-quality gravel deposits in and near Illinois most responsible for excessive freeze-thaw expansion in the test beams. It is difficult to distinguish varieties of chert most related to increased expansion from nonexpansive varieties of chert without making specific gravity separations. Some potentially deleterious rock types, such as shale and conglomerate, are present in such small quantities in test samples that their effect on expansion could not be fully evaluated.

° Expansive rock types, particularly chert, generally are less abundant in the thick, coarse gravels associated with outwash plains in northeastern

Illinois. They are more abundant in valley-train outwash deposits, and their abundance increases downstream.

° Nonexpansive rock types in the gravels studied are the relatively locally derived dolomite, and the less abundant, distantly derived igneous and metamorphic rock types.

° All gravel pits that are sources of high quality gravel aggregate in and near Illinois occur in Wisconsinan age glacial outwash deposits of the Henry Formation.

Phase I point-count data

° Multiple regression analysis of the relationships between rock type amounts found in the slabs cut from Phase I test beams and their freeze-thaw expansion values indicates that: (a) freeze-thaw expansion is more related to chert content than to the content of any other individual rock type; (b) model A (table 9) consisting of chert, ironstone, silty dolomite, and sandstone-siltstone point-count data are more strongly related to expansion than is chert alone; (c) model B (table 9) consisting of chert, ironstone, and metagraywacke point-count data are more strongly related to expansion than the preceeding model when averaged rock-type data and expansion data from the triplicate sets of freeze-thaw test beams are used instead of data from individual beams; and (d) the fact that expansion decreases as dolomite content increases and other rock types decrease, indicate that dolomite has a neutral effect on expansion.

° The routine aggregate quality test results from the IDOT Materials Testing Laboratory were related, using simple regression analyses, with the percentage of expansion values of the Phase I test beams. The relationship of low specific gravity (<2.35) chert with expansion is very highly significant (Prob > F less than 0.001), whereas the total chert data, specific gravity data of the total sample, and high specific gravity (>2.35) chert data show a slightly less significant relationship (Prob > F between 0.01 and 0.001) with freeze-thaw expansion.

° The only abundant deterioration feature found during petrographic study of the slabs cut from the Phase I test beams is cracking concentrated in the expansive pebbles and surrounding matrix cement. Nearby innocuous pebbles can also be fractured by excessive stresses caused by expansive pebbles. Chert pebbles are consistently the most cracked (55% average) of all rock types. This high percentage confirms the finding that high specific gravity (>2.35) chert pebbles also are expansive, but in general not so expansive as low specific gravity (<2.35) chert.

° Expansive pebbles near the surface of a test beam may cause a popout without causing expansion, but those in critical positions deep within the central core of the test beam may contribute strongly to expansion without causing a popout.

° The majority of popouts in the test beams are caused by chert pebbles, followed by ironstones and smaller numbers of weathered carbonates and

silty dolomites. However, the popout data does not correlate very well with the expansion of test beams, nor with the susceptibility of pavements to "D-cracking".

- The 16 gravel samples (15 sources) tested appear to be representative of the rock types present in pits in Illinois that produce high-quality gravel. The rock-type variations among samples are within expected ranges because they are similar to variations found in other studies in the source areas and follow trends that reflect geologic processes.

Phase II gravel separation data

- Statistical analyses of the Phase II groups of rock types and freeze-thaw expansion data indicate: (a) chert is the only abundant (content consistently greater than 5%) rock type that is related to freeze-thaw expansion; (b) dolomite, igneous rocks, and metamorphic rocks are not associated with expansion; (c) minor rock types that probably cause expansion are ironstone, silty dolomite, and possibly weathered carbonate; and (d) cherty carbonate, pyritic dolomite, sandstone-siltstone, conglomerate, and shale are considered suspect only. Weathered schistose, and weathered fine felsic should also be considered possibly suspect, as should any weathered rock, but they probably do not cause significant expansion at the low contents in the study samples.

- Ironstone is related to increased expansion, more than any other rock type in group 5, although it ranges only from a trace to 1.5 weight percent in the samples. The rarity of certain rock types in group 5 makes it difficult to fully evaluate them because when the test beams are cast, it is unlikely that such a small percentage of the original sample will be evenly distributed in amount or placement within the triplicate test beams. The highly significant relationships indicated statistically for group 5 rock types should be used with caution. This becomes very critical to the interpretation of the test results when only a few pebbles can cause significant expansion, or even break a beam.

- The number of chert pebbles in popouts in Phase II chert test beams was more strongly related to expansion values than was the case in the Phase I gravel test beams. Binocular observations of chert pebbles exposed in popouts in Phase II chert (group 1) test beams reveal that brittle porcelaneous cherts are the most abundant type. Many porous porcelaneous cherts are also found in popouts, while waxy vitreous cherts are seldom found in popouts and rarely, if ever, cause them. No determination of the relative abundances of these chert types was possible; nor was it possible to determine how specific gravity variations relate to these types of chert.

- These conclusions apply only to high-quality gravel sources used in Illinois Portland cement pavements and the percentage of the rock types found in the study samples. Gravel deposits used in other states containing gravel derived from different bedrock units and different percentage ranges of rock types should be evaluated independently.

Applications of rock-type data to pit operations

- In a group of samples from the Rock River valley, greater percentages of broken chert and smaller percentages of low specific gravity chert, possibly caused by crushing, are related to lower average freeze-thaw expansions. The lowest expansion values were achieved with gravel processed through a vertical impact crusher. Downstream variations in the valley train systems may also be factors in the differences in rock-type content between samples.

- Differences in expansion values from two gravel sources in the Fox River valley may be related to horizontal and vertical variations in the gravel contents of various parts of the deposit and associated variations in the kinds of rocks in the gravel fraction.

RECOMMENDATIONS

IDOT and the construction aggregate industry should continue to work together in the public interest to eliminate "D-cracking" from occurring in new highway construction projects. The freeze-thaw test is helping to achieve this goal, but problems still persist. Additional governmental and industrial research is needed to:

- Determine the varieties or specific gravity ranges of chert that are most susceptible to freeze-thaw expansion. We suggest that a series of freeze-thaw tests be performed on beams containing constant amounts of chert, separated according to certain ranges of specific gravity, and the results studied according to the petrography of the chert before testing and its condition in the test beams after testing.

- Determine the number of beams that need to be tested per gravel source to overcome the variability of the expansion values, thus raising the statistical significance of the data to acceptable levels.

- Conduct experiments into alternate methods of constructing test beams that may overcome the problem of highly variable expansion values:

  Increase the dimensions of the test beams from 3"x4"x15" to the maximum recommended size of 5"x5"x15" (ASTM, 1979b, p. 385), thus increasing the number of gravel particles in the beams, and perhaps allowing for a more representative sample of the various rock types in each beam. Increasing the volume of the beams might also increase the critical volume of the central core of the beams centered around their axial lines, and decrease the effects of individual pebble locations on expansion values.

  Experiment with different ways of embedding the measuring pins so that the effects of expanding pebbles near their heads are minimized.

  Eliminate the plus 3/4-inch size-fraction, because it contains far too few particles to provide lithologically representative samples in each beam, and because the larger deleterious particles may have disproportionately large effects on test beam expansion values. That such

an effect is real is suggested by Stark and Klieger (1974) and previous IDOT test results that show for the same aggregate source, finer size gradations are usually less expansive than coarser ones.

Experiment with different concrete mixing and test-beam casting techniques.

° Determine if certain processing techniques, such as the vertical impact crusher, can selectively eliminate significant amounts of expansive rock types. This kind of information could help gravel producers design modifications of their processing plants in order to produce higher quality gravel aggregate.

° Determine if variations exist in the distribution of gravel and associated rock types in deposits that experience highly variable freeze-thaw expansion values in different samples, and between closely associated pits.

REFERENCES

Anderson, R. C., 1967, Sand and gravel resources along the Rock River in Illinois: Illinois State Geological Survey, Circular 414, 17 p.

American Society for Testing and Materials, 1979a, Standard descriptive nomenclature of constituents of natural mineral aggregates: Annual Book of ASTM, Philadelphia, PA, Part 14, C294-69, p. 197-205.

American Society for Testing and Materials, 1979b, Standard test method for resistance of concrete to rapid freezing and thawing: Annual Book of ASTM, Philadelphia, PA, Part 14, C666-77, p. 383-388.

Bates, Robert L., and Julia A. Jackson [eds.], 1980, Glossary of geology, 2nd ed.: American Geological Institute, Falls Church, VA, 751 p.

Brewer, Roy, 1964, Fabric and mineral analysis of soils: John Wiley & Sons, New York, NY, 470 p.

Dolar-Mantuani, Ludmila, 1983, Handbook of concrete aggregates, a petrographic and technological evaluation: Noyes Publications, Park Ridge, NJ, 345 p.

Illinois Department of Transportation, 1979, Standard specifications for road and bridge construction: IDOT, Springfield, IL, adopted October 1, 1979, 813 p.

Klieger, Paul, Gervaise Monfore, David Stark, and Wilmar Teske, 1974, D-cracking of concrete pavements in Ohio: Portland Cement Association, Research and Development Laboratories, Cement and Concrete Research Institute, Skokie, Illinois, Report No. OHIO-DOT-11-74, 182 p.

Kneller, W. A., H. F. Kriege, E. L. Saxer, J. T. Wilband, and T. J. Rohrbacher, 1968, The properties and recognition of deleterious cherts which occur in aggregate used by Ohio concrete producers: University of Toledo, Toledo, OH, 201 p.

Lineback, J. A., 1979, Quaternary deposits of Illinois: Illinois State Geological Survey map, 1:500,000.

Lineback, J. A., 1981, Quaternary deposits of Illinois: Illinois State Geological Survey map, 1:2,500,000.

Masters, John M., 1983, Geology of sand and gravel aggregate resources of Illinois: Illinois State Geological Survey, Illinois Mineral Notes 88, 10 p. Extracted from Goodwin, Jonathan H. and John M. Masters, 1983, Geology of aggregate resources of Illinois: in Ault, Curtis H., and Gerald S. Woodard [eds.], Proceedings of the 18th Forum on the Geology of Industrial Minerals: Indiana Geological Survey, Occasional Paper 37, p. 61-90, Bloomington, Indiana.

Masters, John M., 1978, Sand and gravel and peat resources of northeastern Illinois: Illinois State Geological Survey Circular 503, 11 p.

Moorhouse, W. W., 1959, The study of rocks in thin section: Harper & Row, New York, NY, 514 p.

Pettijohn, F. J., 1957, Sedimentary Rocks, 2nd ed.: Harper & Brothers, New York, NY, 718 p.

Pirsson, Louis V., and Adolph Knopf, 1947, Rocks and rock Minerals, 3rd ed.: John Wiley & Sons, Inc., New York, NY, 349 p.

Stark, David, 1976, Characteristics and utilization of coarse aggregates associated with D-cracking: Portland Cement Association, RD047.01P. Reprinted from "Living with marginal aggregates," STP 597, American Society for Testing and Materials, Philadelphia, PA, p. 45-58.

Stark, David, and Paul Klieger, 1974, Effect of maximum size of coarse aggregate on D-cracking in concrete pavements: Portland Cement Association, RD023.01P. Reprinted from Highway Research Record No. 441, "Grading of concrete aggregates:" Highway Research Board Washington, DC, 1973, p. 33-43.

Statistical Analysis System, 1982 ed., User's Guide: Basics: SAS Institute Inc., Box 8000, Cary, NC, 921 p.

Statistical Analysis System, 1982 ed., User's Guide: Statistics: SAS Institute Inc., Box 8000, Cary, NC, 584 p.

Traylor, M. L., 1982, Efforts to eliminate D-cracking in Illinois: Transportation Research Record, No. 853, p. 9-14.

Willman, H. B., and J. C. Frye, 1970, Pleistocene stratigraphy of Illinois: Illinois State Geological Survey Bulletin 94, 204 p.

Willman, H. B., 1973, Geology along the Illinois Waterway--a basis for environmental planning: Illinois State Geological Survey Circular 478, 48 p.

Wonnacott, Thomas H., and Ronald J. Wonnacott, 1981, Regression: a second course in statistics: John Wiley & Sons, New York, NY, 556 p.

APPENDIX

Rock type descriptions

Dolomite (DS) (photo 1). Dolomite pebbles are usually the most abundant rock type in high-quality gravel deposits in and near Illinois. They are mostly light tan to medium gray, fine to coarsely crystalline, dense, and hard. Some are vuggy, with porosity up to 20 percent. In general, dolomite pebbles have a massive texture and blocky fracture, but some are fossiliferous.

Dolomites can range in composition from the pure mineral dolomite ($CaMg(CO_3)_2$) to moderately calcitic dolomite, which contains decreasing amounts of magnesium. It is estimated that the MgO content of rocks identified as dolomite may range from 10 to 22 percent. The distinction between dolomite and limestone is made with a scratch and acid test. Pebbles are first scratched to generate some powder, then tested with dilute HCl. Dolomites give weak to moderate effervescence, especially in the powder generated by the scratch test. Only particles that give vigorous effervescence, independent of the powdery scratch, are considered limestones. Constituents other than carbonate minerals may include up to 10 to 20 percent sand, silt, and clay. Pebbles that contain any identifiable secondary silica or chert are classified as cherty carbonates (CCB). Inclusions of asphaltic residues are occasionally present. A few pebbles contain 10 to 20 percent glauconite pellets.

Dolomite pebbles in Illinois gravel deposits were derived from marine strata of Paleozoic age. These strata were originally deposited as limestones, but were subsequently dolomitized by the partial replacement of calcium with magnesium, altering calcite to the mineral dolomite.

Laminated Dolomite (LD) (photo 2). Laminated dolomite pebbles are more than 80 percent dolomite mineral, and they contain partings, laminae, lithologic variations or other planar elements. A pebble may contain one or many such features which may be continuous or discontinuous, parallel, wavy, contorted, or even intersecting. In some cases laminations appear to be a result of bedding or grain-size variation in otherwise homogeneous dolomite; in others they are caused by intercalated sand, silt, clay, carbonaceous material or fossil debris. One rare fossiliferous variety contains thin, elongate, dark gray to black bryozoan fragments, arranged along discontinuous layers. A few laminated dolomite pebbles contain veins of calcite; others contain stylolites. Laminated dolomite pebbles that contain more than about 20 percent sand, silt, and/or clay are classified as silty dolomites (SD).

Silty Dolomite (SD) (photo 3). Silty dolomite pebbles are dolomites, with 20 to 50 percent quartz silt or sand grains. They feel and look gritty. The presence of abundant quartz grains is often revealed when a pebble is scratched with the hardness tester and a discontinuous metal streak is produced. As the silt content goes up the scratch test produces decreasing amounts of dolomite powder and a more continuous metallic streak. Silty dolomites are usually slightly oxidized, slightly to moderately porous, and quite frequently laminated.

<u>Pyritic Dolomite</u> (PD) (photo 4). Pyritic dolomite pebbles are dolomite with pyrite inclusions (always less than 5% and usually less than 1%). The inclusions commonly occur as euhedral cubic crystals, fine-grained disseminated granules, or as a replacement mineral in the pyritization of fossils, or combination of these forms. The pyrite is often oxidized and weathered to a mass of iron hydroxide and/or iron-stained crystal impressions, and it often occurs at the center of cone-shaped fractures in the pebbles, closely resembling popouts in the surface of Portland cement concrete.

<u>Limestone</u> (LS) (photo 5). Limestones are composed almost entirely of the mineral calcite ($CaCO_3$). The chief criterion for identifying limestones is the instantaneous, vigorous, effervescent reaction with dilute HCl on the unscratched surface. Chemically, limestones may contain trace amounts of dolomite, usually amounting to less than about 2 percent MgO. The mineral calcite is slightly softer than the mineral dolomite; thus, in general, limestones can be scratched more easily than dolomites. Constituents other than calcite may include moderate amounts of clay, silt, or sand. Argillaceous limestones remain limestone provided the clay content does not render the rock soft or crumbly and the acid reaction is still vigorous. Sandy and silty limestone remains limestone up to the point where the calcite is present only as a cementing agent, in which case the rock is a sandstone. Even trace amounts of chert make the rock cherty carbonate (CCB). Limestones are usually light to dark gray, but can be tan, brown, olive, cream, or pink. Porosity is generally low, but when a limestone is highly porous it is usually classified as a weathered carbonate (WCB).

Limestone pebbles in the study samples are from marine strata of Paleozoic age. They originated as biochemical (fossils) or chemical precipitates of aragonite or calcite. Many limestones originated as fragmental or detrital calcite that was mechanically transported and deposited; others grew (e.g., corals) in place or were precipitated and settled out of suspension.

<u>Cherty Carbonate</u> (CCB) (photo 6). Cherty carbonate pebbles are composed of limestones or dolomites intermixed with chert. The chert content ranges from only a trace up to 50 percent. The most frequently encountered variety of cherty carbonate is a limestone or dolomite containing fossils that have been silicified (replaced by chert). The main mass of such a particle is carbonate and powders when scratched. The cherty fossil inclusions cannot be powdered, and will retain a metallic streak as the scratching tool passes over. In other pebbles, the cherty phase and carbonate phase are indistinguishable, the silica being disseminated throughout the carbonate; these will react with dilute HCl according to the type of carbonate present. For a pebble that would otherwise qualify for a limestone, dolomite, or any other carbonate category, the presence of chert takes precedence and makes the rock a cherty carbonate (e.g., a porous, crumbly, weathered dolomite with a few scattered silicified crinoid columnals is cherty carbonate, rather than weathered carbonate).

<u>Chert</u> (CH) (photo 7). Chert pebbles are composed of 50 percent or more microcrystalline or cryptocrystalline quartz. Other components are mainly limestone or dolomite, but may be other sedimentary rock types. Usually chert is extremely hard, dense, and massive, and breaks with a conchoidal fracture. Color variation is exceptionally large and includes white, gray, green, blue, pink, red, yellow, brown, and black. Color patterns are likewise complex,

ranging from solid to mottled to banded. Many pebbles have a glossy patina in shades of brown, red, or black that are quite different from their interiors. Some types are translucent, and others are opaque. Luster varies from porcelaneous to waxy. Texture varies from porous to dense. Some of the more common types include chalcedonic chert, agate, porous chalky chert, porcelaneous chert, fossils replaced by chert, and fine-grained flinty chert. Pebbles of coarsely crystalline quartz intergrown with microcrystalline or chalcedonic quartz were originally quartz geodes and are classified as cherts even if the chalcedonic part comprises less than 50 percent of the pebbles. Chert pebbles do not react with dilute HCl, unless they contain inclusions of calcite or dolomite. A more or less continuous metallic streak is produced when an attempt is made to scratch most chert pebbles; however, the porcelaneous, chalky, and weathered pebbles may be porous and unconsolidated enough to be scratched or gouged.

Chert often occurs as a replacement mineral in rocks by silicification. The original constituents are pervasively replaced by secondary silica or selectively replaced, as when enclosed fossils (e.g., carbonate shells) are replaced by silica. Some chert pebbles are actually silica-cemented aggregates of cherty fossil debris (i.e., arenaceous rocks in which grains and cement are identifiably chert). Some cherts contain fossils and textures that indicate geologic age; however, most of them cannot be associated with any one geologic formation, series, or system.

<u>Weathered Carbonate</u> (WCB) (photo 8). Weathered carbonate pebbles are composed of limestone or dolomite soft enough to gouge or crumble rather than powder when scratch-tested. The gouge of a weathered carbonate rock differs from the scratch of either dolomite or limestone in that the former is deep and wide (about 1 mm x 1 mm or more) and leaves a noticeable scar when the gouged material is rinsed away, whereas the latter leaves behind only a thread-size scratch. Carbonate rock particles that are partly firm and partly soft are classified as weathered carbonate rocks if the soft area constitutes half or more of the total area. If the soft part of the rock is strictly a thin outer coating, it is not considered weathered, and classification is made according to other features. These weathered carbonates are moderately to highly porous and often contain clay-, silt- and sand-size impurities of various mineral compositions (usually quartz). Many of them are laminated. Composition alone occasionally accounts for the degree of softness but usually the processes of weathering seem to be the cause. They are colored in various shades of yellow, orange, and brown by iron-hydroxide weathering products. Marly and clayey particles tend to be lighter colored, ranging from earthy gray to dusky yellow, but are just as soft as the above.

<u>Ironstone and Ocherous Rocks</u> (IO) (photo 9). Ironstones and ocherous pebbles consist predominantly of iron oxide in various states of hydration. Most are porous, clayey or silty, and soft enough to scratch, but some are more dense, compact, and hard to scratch. Colors may range from pale yellow-orange to reddish brown to chocolate brown. Most will stain the fingers when rubbed. Most ironstones are concretionary or nodular and display concentric layering on broken surfaces. Occasionally, a pebble will have a resistant outer rind and softer, more clayey inner material. Some have a concave-convex shape with botryoidal textures on the convex sides, and give the impression of being a fragment of the lining of a cavity. Many of them are weathered siderite concretions from Pennsylvanian shales. Some contain siderite, calcite and/or

pyrite. Iron hydroxide cemented siltstones and sandstones and ferruginous claystones are classified with the ironstones. Ocherous rocks are massive, powdery particles of predominantly yellow or brown iron hydroxide. They may represent the weathered residuum of iron carbonate.

Shale, Mudstone, Claystone, and Coal (SH) (photo 10). Pebbles of the finest grain-size and softest sedimentary particles are grouped into this category, because they are too rare to list separately. They readily disintegrate and thus, when present, are most common in the 3/8-inch to #4-mesh sieve-size. They all gouge easily when scratched.

Shales consist mostly of silt- and clay-size detrital particles. The mineralogy of these particles is dominated by quartz and various clay minerals. They are laminated and often split into thin layers or splinters. Their colors are shades of black, gray, green, red, or brown.

Mudstones and claystones are similar to shales except that they are more massive, and often break with a conchoidal fracture. Mudstones may contain abundant silt, while claystones are predominantly clay. Mudstones tend to be darker colored in shades of gray to black, while claystones are usually lighter shades of gray, green or buff. Some claystones are composed essentially of clay-sized quartz grains. Shales, mudstones, and claystones may contain minor amounts of carbonate. Mottling of colors may also occur in either shales, mudstones, or claystones. The black rocks in this category frequently are high in organic content (e.g., carbonaceous black shales). Coaly shale and true coal are occasionally found. The occurrence of coal in a sample is noted in the section of this report where that sample is described.

Sandstone-siltstone (SS) (photo 11). Pebbles of sandstone and siltstone are loosely to tightly cemented, poorly to well-sorted, sand- to silt-sized detrital sediments of variable composition. Quartz is the predominant type of grain, with accessory amounts of rock fragments, feldspars, micas, clays, and carbonates, and less commonly organic matter, glauconite, and other constituents. Silica is the most common cementing agent, but calcite and clay also occur. Iron-oxide cemented sandstones or siltstones are classified as ironstones (IO). Poorly cemented pebbles are friable. Porosity varies with composition and with type and degree of cementation, ranging from highly porous in the loose micaceous Pennsylvanian sandstones to nonporous in the dense silica-cemented silstones. Massive types occur, but more commonly cross bedding, banding, burrows, laminations, or other structures typical of stratified granular sediments are present. Siltstones and sandstones are highly variable in color; however, they are mainly varieties of cream, khaki, gray, brown, and red. Sandstones with abundant quartz grains that are frosted or have overgrowths are off-white or even sparkly silver-white if they contain abundant muscovite flakes. Carbonaceous sandstones can approach grayish black. When weathered, sandstones and siltstones can be orangish red to dark reddish brown.

Conglomerate (CG) (photo 12). Pieces of conglomerate consist of heterogeneous mixtures of subangular to rounded, granule (rock fragments) to sand-size (quartz), loosely to moderately well-cemented clastic particles. The cementing agent is almost exclusively calcite, which may be clayey, but sometimes the cement is iron hydroxide. Porosity and friability are directly related to the degree of cementation. Most are very porous, loosely bonded and friable.

Conglomerate occurs in either of two forms: (1) individual pebble-sized pieces of conglomerate, or (2) pebbles of another rock type (commonly dolomite or limestone) which are incompletely encased by conglomerate. In the latter case, if not more than 25 percent of the host pebble is covered, the conglomerate is ignored and the host rock is classified as usual. Conglomerate particles are interpreted to have been cemented during Quaternary time because of the localized precipitation of calcite from the groundwater percolating through gravel deposits.

Mafic (MA) (photo 13). Mafic pebbles are igneous rock types that range from very fine-grained (aphanitic) basalt to coarse-grained gabbro and diabase. Porphyritic and ophitic textures are common. They are medium to dark gray, light to dark greenish gray, dark purplish gray, or black, and are composed mainly of plagioclase feldspar and ferromagnesian minerals such as hornblende and biotite. Less common minerals are pyroxene, magnetite, hematite, olivine, and others. Some basalts contain vesicles that are often filled with secondary materials such as agate. When a metamorphic fabric is present (alignment or preferred orientation of mineral grains), mafic pebbles may be classified as gneiss (G) or, if fine grained and bladed, as schistose metamorphics (BM).

These pebbles are derived from mafic igneous bodies such as lava flows, dikes, and sills in the Canadian Shield, especially in the Lake Superior region.

Coarse Felsic (CF) (photo 15). Coarse felsic pebbles are derived from igneous rocks that are rich in feldspar and silica and have individual crystalline mineral grains that are distinguishable with the naked eye or hand lens (phaneritic texture). Most commonly they are medium to coarse grained. These pebbles normally are light in color, ranging from milky white and tan to shades of light red and pink. Most have an equigranular texture with interlocking crystalline minerals. The minerals show neither alignment nor banding. Prophyritic and graphic textures also occur. In general, coarse felsic rocks have the composition of granites or similar light colored, coarse-grained igeneous rocks that contain various amounts of quartz, feldspar, feldspathoids and muscovite (nepheline syenite, syenite, quartz monzonite). Their ferromagnesian mineral content is generally less than 10 percent. Single crystals of feldspar are placed in this category. Pebbles of felsic composition that contain noninterlocking mineral grains or other such metamorphic or deformation features are classified as gneisses (G). This restriction on coarse felsics has resulted in lower "granite" contents than other workers have reported in Illinois gravels; however, we believe this restriction was necessary to evaluate the possibility that such features might be zones of weakness that could contribute to "D-cracking." These pebbles are derived from the widespread, Precambrian, plutonic igneous rock complexes, such as pegmatites or batholiths, of the Canadian Shield.

Fine Felsic (FF) (photo 17). Fine felsic pebbles are derived from igneous rock so fine grained that minerals are below resolution of the naked eye or low magnification binocular microscope (aphanitic texture). Typically they are porphyritic and contain phenocrysts of feldspar and quartz embedded in the aphanitic groundmass. They are relatively light in color, usually shades of red, but sometimes purple, brown or gray. Compositionally, the majority of these pebbles are rhyolite, the extrusive equivalent of granite. Others, which have decreased amounts of orthoclase (potassium) feldspar and

crystalline silica (quartz), and increased amounts of plagioclase (sodium-calcium) feldspar, are quartz latites and rhyodacites.

Most fine felsics have a massive or stony appearance with the phenocrysts randomly oriented within the groundmass, but some exhibit flow banding or more complex and fragmental textures suggestive of flow breccia. Small amounts of devitrified volcanic glass, ash and pyroclastic material are often incorporated into these rocks. A few contain vesicles of variable size. These pebbles are essentially unmetamorphosed extrusive igneous rocks derived from the late Precambrian of the Canadian Shield, mainly in the Lake Superior region.

Massive Crystalline Quartz (MQ) (photo 19). Massive crystalline quartz pebbles are composites of large interlocking quartz crystals. They contain more than 90 percent quartz. They are very hard, have a vitreous luster, and break with a conchoidal fracture. Most are translucent to some degree with variable color tints of milky white, smoky gray, pinkish gray, and yellowish tan. Most of these pebbles are believed to be quartz vein material from the metamorphic and igneous terrain of the Canadian Shield. Others may be from granite pegmatites, or quartzites metamorphosed to the extent that no sedimentary features remain. A few may be derived from the crystalline centers of quartz geodes.

Gneiss (G) (photo 20). For the purposes of this study, the category of gneiss has been broadened to include rock types with lower grade metamorphic features than are normally associated with rocks bearing the name gneiss.

Gneiss pebbles are derived from fine- to coarse-grained crystalline metamorphic rocks. Included in this category are the typical gneisses in which some or all of the minerals are aligned, often into alternating light and dark colored bands. The light bands tend to be granulose in texture and felsic in composition, with quartz and feldspar predominant. The dark bands tend to be schistose in texture and mafic in composition, usually containing hornblende and/or biotite. In addition to these banded types, there are coarse-grained metamorphic rocks included in this category which show neither banding nor mineral alignment. Instead, they have other metamorphic features such as cataclastic grain boundaries and recrystallization features.

Many gneiss pebbles have the overall composition of a granite but are classifed gneiss because of textural evidence of metamorphism. Some gneissic pebbles have a "mafic" composition but are classified as gneisses due to alignment or banding of minerals.

With decreasing crystal size, pebbles in this category may grade into metasedimentary (MS) types if sedimentary features are present. They may also grade into bladed metamorphics (BM), or schistose rocks, as very fine-grained crystals of minerals such as chlorite, mica, and hornblende predominate, resulting in bladed or schistose textures.

These rocks originate in the wide-ranging assemblages of Precambrian metamorphic rocks of the Grenville and Superior Provinces of the Canadian Shield.

Schistose Metamorphic (Bladed, Banded, Foliated) (BM) (photo 22). Bladed, banded, foliated, and schistose metamorphic pebbles are composed mainly of

ferromagnesian minerals such as hornblende, biotite, and chlorite that are platy, flaky, or bladed in shape. The crystals are arranged in thin, leaflike layers or lenses with parallel orientation, which give the pebbles a strong planar fabric. These pebbles are very fine-grained and even-textured relative to gneisses. They usually have a platy shape, and are dark greenish gray to black in color. They are derived from the dynamically metamorphosed Precambrian terrain of the Canadian Shield.

Metasediment (MS) (photo 24). Metasedimentary pebbles are derived from metamorhic rock units in which the metamorphism is of low enough grade that evidence of their sedimentary origin is preserved. Most formed from detrital sedimentary rocks having a wide range of textures and compositions; some formed from chemically precipitated sedimentary rocks.

Metasedimentary pebbles tend to be siliceous, hard, dense, and nonporous. Most are massive, but sedimentary bedding can be identified in some pebbles. Grain size may vary from extremely fine to coarse. Virtually all colors occur. Crystallization and growth of true metamorphic minerals are usually not far enough advanced to be visible. However, secondary enlargement of grains and pressure solution features are often present. Development of metamorphic foliation and cleavage is minor.

Many rock types are included in this category. Among these are metamorphosed arkoses, siltstones, argillaceous rocks, and the distinctive iron formations rich in jasper, hematite, and iron silicate minerals. Certain distinct types of metasediments occurred frequently and were quite abundant. To accomodate these types, separate categories were established. These special metasedimentary rock types are tillites, metagraywackes, and quartzites. Many pebbles that were derived from metamorphosed sandstones, but contain too much nonquartz material to be classified as quartzites, were retained in the metasedimentary category.

Many of the pebbles in this category, as well as those in the metasedimentary types given separate categories as mentioned above, are believed to have originated from the Huronian Supergroup, a widespread succession of Proterozoic age in the Southern Province of the Canadian Shield.

Metagraywacke (MGY) (photo 26). Metagraywackes are greenish gray to dark gray, firmly indurated, poorly sorted, clayey sandstones which have undergone low-grade metamorphism. They generally have a biomodal, or two-phase, distribution of particle sizes in which angular to subangular sand grains are embedded in a finer grained matrix. An average composition of the sandy material is 70 percent quartz (clear, smokey, or milky), 20 percent plagioclase feldspar, and 10 percent mafic and other rock types. When a pebble is wet, these larger angular grains of milky quartz and plagioclase become quite conspicuous. The finer grained matrix between the grains of sand consists of a compact mixture of silt- and clay-size particles. The composition and poorly sorted nature of these rocks, and the occasional presence of graded bedding and cross bedding, indicate they could be turbidities--rocks formed from rapid and turbulent submarine flows of sediment-laden water. Alternatively, they may represent sands which are mineralogically very immature, or they may have been deposited under glacial conditions and would thus be related to the tillites. The presence of an occasional grain of bright red jasper suggests these pebbles could be associ-

ated with the Gowgonda or Lorrain Formations (Precambrian) of the Canadian Shield.

Tillite (T) (photo 27). Tillite pebbles consist of low-grade metasediments approximating silty to sandy mudstones in composition. They have a massive texture and medium gray color when dry. When wet, the clayey matrix takes on a distinctive greenish gray to bluish gray appearance. Within this silty clay matrix, tillites have floating angular sand or larger sized particles, often lithic (rock fragment) in nature. Clear to smoky quartz is usually most abundant, but other detrital particles often found include feldspar, granite, gneiss, schist, and diabase. Quartz sand content may be as high as 30 percent, and rock fragment content is usually less than 10 percent but may be as high as 20 percent. The matrix is less resistant to abrasion and weathering than the sand; thus, sand grains may stand out in relief, or may be plucked out. Tillites are generally nonreactive to dilute HCl.

These rocks are interpreted to have been deposited as glacial tills, which were later altered to low metamorphic grade rocks. They are thought to originate from the Precambrian rocks of the Canadian Shield, in particular the Gowgonda Formation.

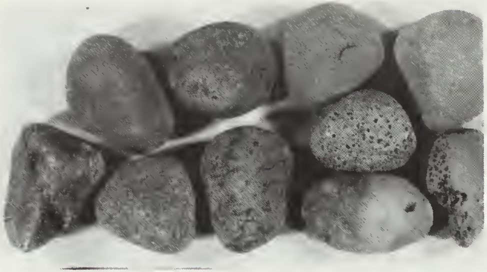
Quartzite (Q) (photo 28). Quartzite pebbles are metamorphosed sandstones that contain more than 90 percent interlocking quartz sand grains. They are very hard, highly indurated, nonporous, and nonpermeable. They break across the quartz grains rather than around them, as in sandstones. Their colors vary from dark red to milky white, and often they are translucent. If no sand grains are distinguishable, the pebbles are classified massive crystalline quartz (MQ).

These pebbles are derived from Precambrian rocks of the Canadian Shield. Many are Baraboo Quartzite from the Baraboo Range of Wisconsin. A few contain grains of jasper, indicating that they are from the jasper-conglomerate facies of the Lorrain Formation of Ontario.

Igneous and Metamorphic Weathered Rock Categories - General Description (WMA, WCF, WFF, WG, WBM, WMS) (photos 14, 16, 18, 21, 23, 25, respectively). Rock categories carrying the weathered modifier include rocks which are identified to be of the base category but are soft, crumbly, or flaky because of the effects of weathering. Oxidation of the mafic rocks often imparts an orangish cast to them. The weathering or alteration of felsic rocks often gives them a dusky, dirty appearance. Weathered mica-rich rocks tend to be flaky. Weathered schistose, bladed, or foliated rocks tend to become fissile. Deeply weathered tillite (T) or metagraywacke (MGY) pebbles are extremely rare, but when present are grouped with the weathered metasedimentary pebbles (WMS).

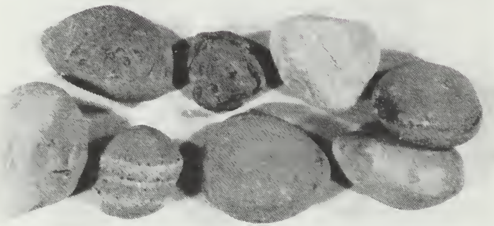
Rock-type photos

1. Dolomite
2. Laminated dolomite
3. Silty dolomite
4. Pyritic dolomite
5. Limestone
6. Cherty carbonate
7. Chert
8. Weathered carbonate
9. Ironstone
10. Shale
11. Sandstone-siltstone
12. Conglomerate
13. Mafic
14. Weathered mafic
15. Coarse felsic
16. Weathered coarse felsic
17. Fine felsic
18. Weathered fine felsic
19. Massive crystalline quartz
20. Gneiss
21. Weathered gneiss
22. Schistose metamorphic
23. Weathered schistose metamorphic
24. Metasediment
25. Weathered metasediment
26. Metagraywacke
27. Tillite
28. Quartzite.

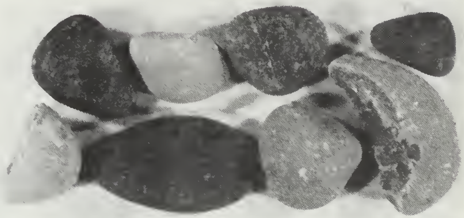


1 Dolomite

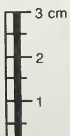
4 Pyritic Dolomite

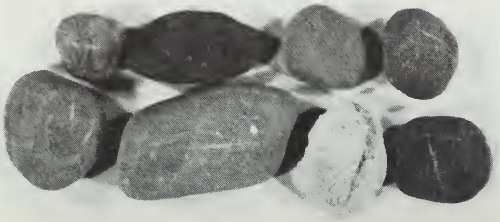


2 Laminated Dolomite

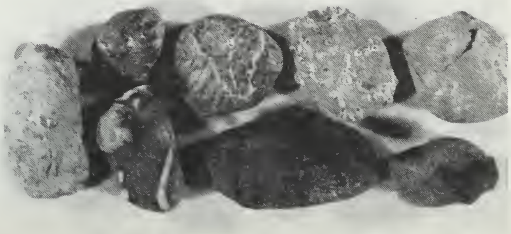


5 Limestone



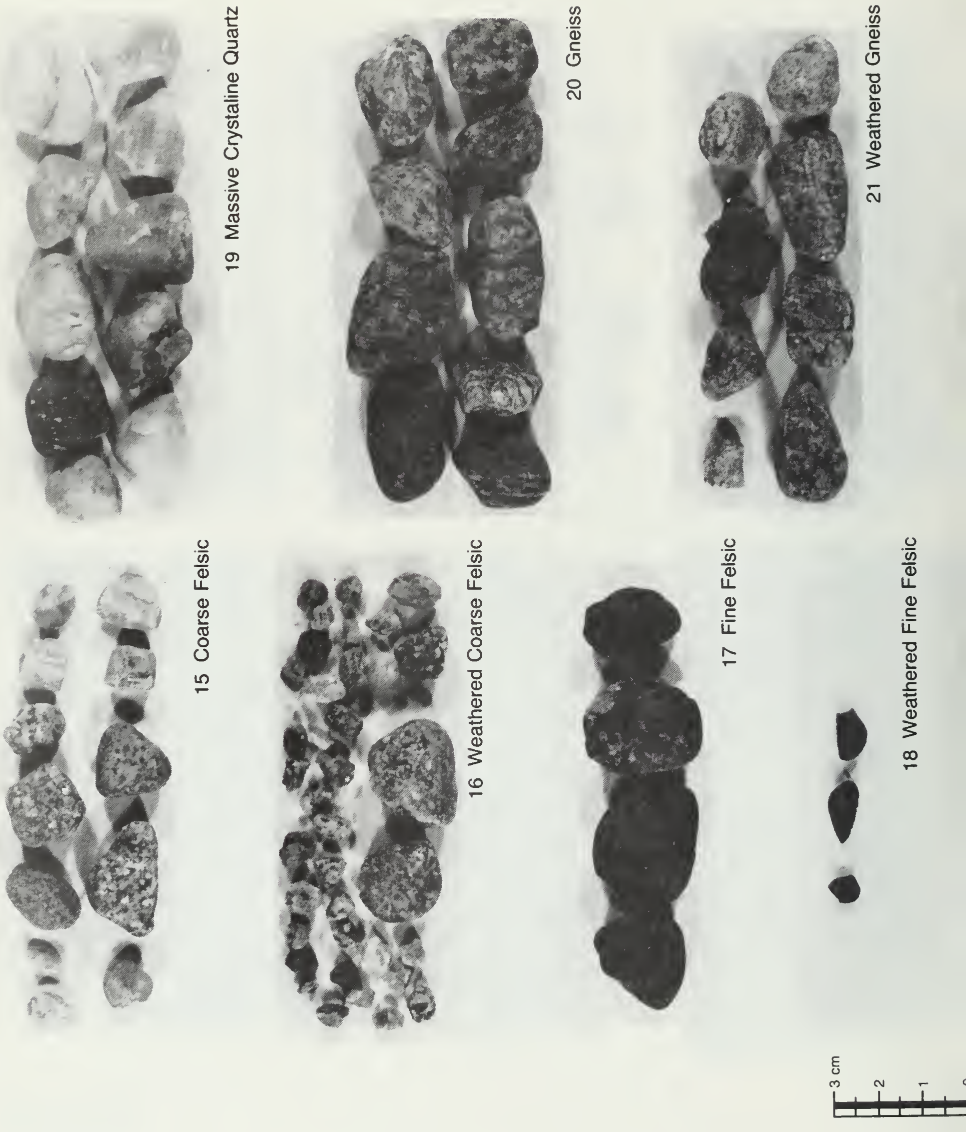


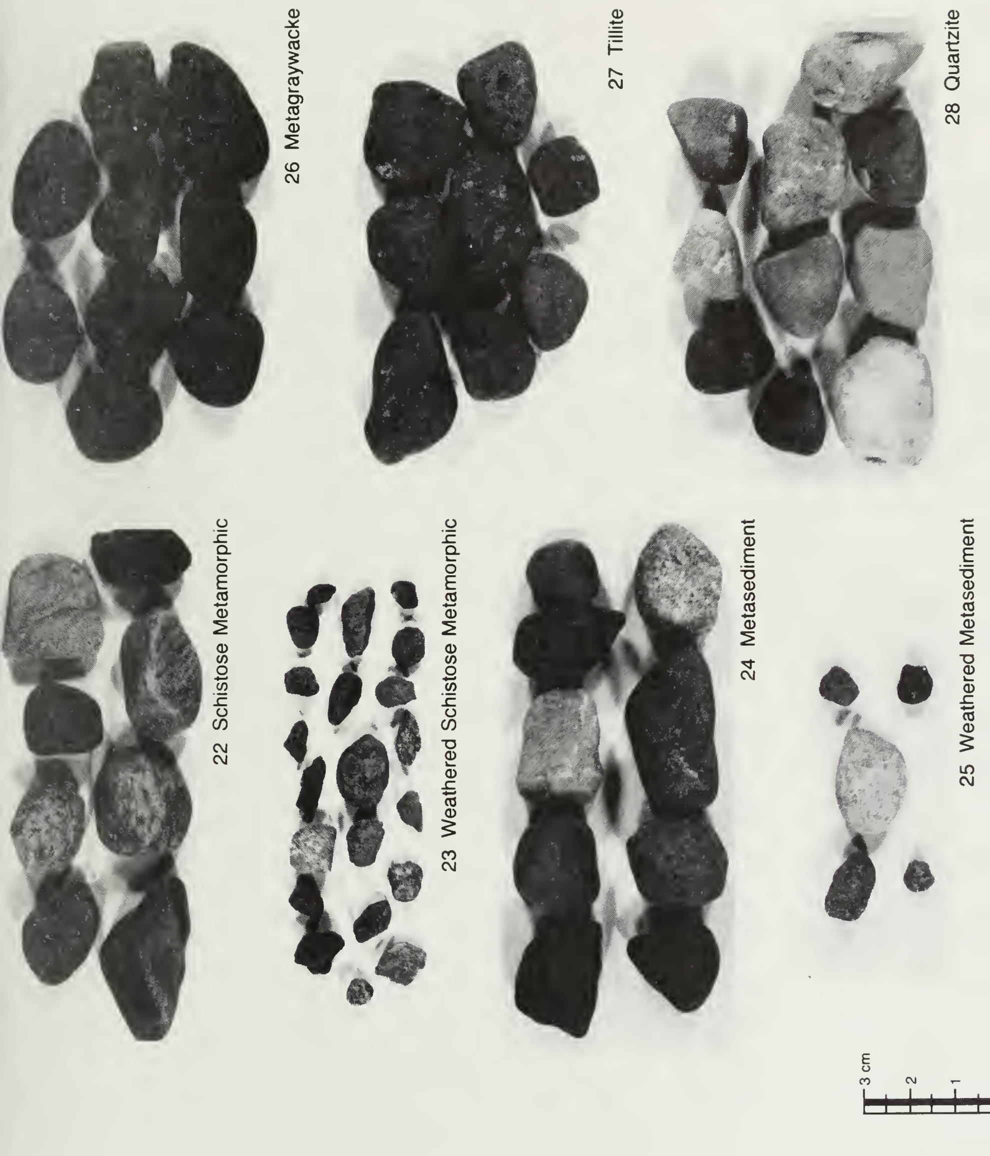
3 Silty Dolomite



6 Cherty Carbonate

11 Sandstone-Siltstone
12 Conglomerate
13 Mafic
7 Chert
8 Weathered Carbonate
9 Ironstone
3 cm
2
1


19 Massive Crystaline Quartz
20 Gneiss
21 Weathered Gneiss
15 Coarse Felsic
16 Weathered Coarse Felsic
17 Fine Felsic
18 Weathered Fine Felsic
3 cm
2
1


22 Schistose Metamorphic
23 Weathered Schistose Metamorphic
24 Metasediment
25 Weathered Metasediment
26 Metagraywacke
27 Tillite
28 Quartzite
3 cm
2
1